U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-265 842

Evaluating Economic Impacts of Programs for Control of Saline Irrigation Return Flows A Case Study of the Grand Valley, Colorado

Colorado State Univ, Fort Collins. Dept. of Economics

Prepared for

Environmental Protection Agency, Denver, Colo. Region VIII

30 Jun 76

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE

Evaluating Economic Impacts of Programs for Control of Saline Irrigation Return Flows: A Case Study of the Grand Valley, Colorado.

5. REPORT DATE

June 30, 1976

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

Leathers, Kenneth L. and Robert A. Young

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Dept. of Economics
Colorado State University
Fort Collins, CO

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.

Project 68-01-2660

12. SPONSORING AGENCY NAME AND ADDRESS

EPA Region VIII
1860 Lincoln Street
Denver, CO 80295

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Economic impacts of alternative on-farm water management programs for controlling saline irrigation return flows are estimated. The study focuses on the Grand Valley in west central Colorado, an area thought to be representative of irrigation return flow problems in the Upper Colorado River Basin. Direct economic impacts, in terms of increased cost or reduced incomes, are estimated with linear programming models of representative farm situations. A regional interindustry model was developed to trace indirect economic impacts on related economic sectors in the three-county local trade area. Since the hydrologic-geologic relationships which govern salt pick-up in the study reach are not entirely understood, a correlation and regression analysis of water quality and quantity data was performed. This analysis attempted to distinguish salt contributions of natural origin from those due to irrigation, and to separate irrigation concentrations into components attributable to on-farm irrigation practices as compared to water distribution system losses.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
economic analysis water quality irrigation surface irrigation salinity waste water water reclamation	Grand Valley, Colorado Upper Colorado River Basin	

18. DISTRIBUTION STATEMENT Unlimited distribution	19. SECURITY CLASS *(This Report)* unclassified	21. NO. OF PAGES 170 pp
	20. SECURITY CLASS *(This page)* unclassified	22. PRICE MF PC A09 A01

EPA Form 2220-1 (9-73)

PB 265 842

ENVIRONMENTAL PROTECTION AGENCY
ROCKY MOUNTAIN PRAIRIE REGION

EVALUATING ECONOMIC IMPACTS OF PROGRAMS FOR CONTROL OF SALINE IRRIGATION RETURN FLOWS
A CASE STUDY OF THE GRAND VALLEY, COLORADO

JUNE 1976

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EVALUATING ECONOMIC IMPACTS OF PROGRAMS FOR CONTROL OF SALINE IRRIGATION RETURN FLOWS: A CASE STUDY OF THE GRAND VALLEY, COLORADO

By

Kenneth L. Leathers and Robert A. Young
Department of Economics
Colorado State University
June 30, 1976

Project 68-01-2660

Project Officer
Mr. George Collins, Economist
Region VIII
Environmental Protection Agency
Denver, Colorado 80203

ia

ABSTRACT

Economic impacts of alternative on-farm water management programs for controlling saline irrigation return flows are estimated. The study focuses on the Grand Valley in west central Colorado, an area thought to be representative of irrigation return flow problems in the Upper Colorado River Basin. Direct economic impacts, in terms of increased cost or reduced incomes, are estimated with linear programming models of representative farm situations. A regional interindustry model was developed to trace indirect economic impacts on related economic sectors in the three-county local trade area. Since the hydrologic-geologic relationships which govern salt pickup in the study reach are not entirely understood, a correlation and regression analysis of water quality and quantity data was performed. This analysis attempted to distinguish salt contributions of natural origin from those due to irrigation, and further, to separate irrigation contributions into components attributable to on-farm irrigation practices as compared to water distribution system losses.

It was found that, given plausible assumptions about the proportion of irrigation water diversions which percolates into the saline aquifer as drainage water, adjustments in on-farm water management practices are a relatively inexpensive method for reducing salt loading. Other nonstructural alternatives (such as land retirement) and structural approaches (such as lining of canals to reduce seepage) appear to be

considerably more expensive. Downstream benefits (salinity damages avoided) are not judged to be large enough to warrant (on strict economic efficiency grounds) undertaking any of the proposals other than adjustment in on-farm water management.

The statistical analysis of sources of salt pickup lead to the conclusion that natural forces account for considerably more salinity in the study reach than has been heretofore assumed by the public agencies responsible for salinity control. Further, there is some support for the hypothesis that, of the irrigation-related salt loading, leakage from the delivery system is the most significant source. This result, if confirmed by subsequent investigation, has considerable significance for salinity abatement policy in the Upper Colorado Basin.

TABLE OF CONTENTS

ABSTRACT ii

TABLE OF CONTENTS iv

LIST OF ILLUSTRATIONS vii

LIST OF TABLES ix

ACKNOWLEDGEMENTS xi

CONCLUSIONS xii

RECOMMENDATIONS xiv

SECTIONS

I INTRODUCTION

A. Background 1
  Salinity in the Colorado River Basin 1
  Potential Means of Alleviation 5

B. Objective and Plan of Study 6

C. Order of Presentation 7

II THE GRAND VALLEY AS A CASE STUDY

A. Overview 8

B. Irrigated Agriculture 10

C. Return Flow Salinity 11
  Salt Pickup Mechanisms 12
  Proposed Salinity Controls 17

D. Justification 19

III RESEARCH PROCEDURES: CONCEPTS, METHODS AND ASSUMPTIONS

A. Introduction 20

B. Hypothesized Means of Reducing Salinity 21
  On-Farm Control Options 21
  Land Retirement 23

C. Conceptual Framework for Estimating Program Costs 23
Representative Farms and Linear Programming 24
Interindustry Analysis 25

D. Economic Benefits of Reduced Salt Discharge 26

IV THE ECONOMICS OF ON-FARM SALINITY CONTROL

A. Introduction 29

B. Simulating Farmer Response 30
Data Source and Sampling Method 30
The Programming Models and Assumptions 31
Modifications in Irrigation Practices 38

C. Irrigation-Salinity Relationships 41
The Soil-Water-Crop Budget 41
Rate of Salt Pickup in Return Flows 45

D. Results and Summary 54
Estimated Costs for Control of Deep Percolation 54
Estimated Costs of On-Farm Seepage Control 57
Summary and Implications 58

V THE ECONOMICS OF LAND RETIREMENT AS A MEANS OF CONTROLLING SALINE IRRIGATION RETURN FLOWS

A. Introduction 62

B. Approach and Assumptions 64
Compulsory vs. Noncompulsory Programs 64
Partial vs. Complete Retirement 65
Valuation of Land and Water Resources 66
Analysis of Direct and Indirect Impacts 68
Accounting Stance 71

C. Results and Discussion 72
Local Direct and Indirect Costs 72
Implications for the State of Colorado 76

D. Summary of Cost-Effectiveness 77

VI RETURN FLOW SALINITY MECHANISMS: A REAPPRAISAL OF ESTIMATES AND ASSUMPTIONS

A. Introduction 81

B. Review of Previous Research 82
Agricultural Pickup Mechanisms 83
Natural Pickup Mechanisms 87
Implications for Policy Decisions 91

C. Methods of Analysis and Data Selection 93
  The Techniques of Correlation and Regression 94
  Data Sources and Evaluation 95
    Stream Flow and Salinity 95
    Natural Runoff 99
    Irrigation Return Flows 101
  The Empirical Hydro-Salinity Equations 108

D. Results and Discussion 110
  Part I: The Annual Data 110
  Part II: The Monthly Data 128
  Part III: The Quarterly Analysis 139

E. Summary and Implications 144
  Recommendations for Further Research 149

VII APPENDIX

Literature Cited 150

Supporting Information 155

LIST OF ILLUSTRATIONS

FIGURE PAGE

1. The Colorado River Basin 9
2. Cross-Section of Geologic Formations in the Grand Valley . . . 13
3. The Grand Valley of Colorado 15
4. Frequency Distribution of Sample Farm Size and Model Acreage Parameters 32
5. Harvested Acreages of Selected Crops Grown on Bureau of Reclamation Project Lands (Garfield Gravity Division) in the Grand Valley, 1948-1974 34
6. Acreages of Selected Crops as a Percentage of Total Cropped Acres for Model Farms 35
7. The Grand Valley Trade Area 69
8. Grand Valley Reach of the Colorado River 84
9. Annual Estimates of Salt Pickup, Irrigation Water Deliveries to Farms, Precipitation and Net Discharge for the Grand Valley Reach, 1951-1972 111
10. Annual Estimates of Irrigation Diversions, Distribution System Waste Water, Canal and Lateral Seepage Losses, and Crop Evapotranspiration for the Government Highline Canal, 1951-1972 112
11. Data Plots of Net Salt Pickup With Precipitation and Net Discharge: Annual Data 116
12. Data Plots of Net Salt Pickup With Irrigation Diversions and Farm Deliveries: Annual Data 117
13. Data Plots of Net Salt Pickup With Canal Seepage and Deep Percolation: Annual Data 118
14. Monthly Mean Estimates of Net Salt Pickup, Precipitation and Delivered Irrigation Water for the Government Highline Canal, 1951-1972 129
15. Monthly Mean Discharge and Salt Load of the Gunnison River, and Precipitation at Three Locations in the Grand Valley Reach, 1951-1972 130

List of Illustrations, continued

FIGURE PAGE

16. Monthly Means of Seasonal On-Farm Deliveries, Crop Consumptive Use, Field Tail Water, Deep Percolation, Seepage, and Spillage for the Government Highline Cana, 1951-1972 132

LIST OF TABLES

TABLE PAGE

1. Estimates of Additional Labor (Inconvenience) Cost to Farmers for Shifting from Present to More Efficient Irrigation Practices 40

2. Traditional Irrigation Practices and Soil Moisture Relationships for Selected Crops in the Grand Valley 43

3. Water Budget Summary for Traditional Irrigation Practices in the Grand Valley: Annual Water Use and Losses for Selected Crops 44

4. Comparison of Total Water Budgets for Irrigation in The Grand Valley: Aggregate Use and Losses 46

5. Average Composition of Colorado River Water Diverted for Irrigation and Predicted Ionic Equilibrium for Various Leaching Fractions 48

6. Ionic Analyses of Drainage Waters for Selected Drain Outlets in the Grand Valley: Averaged Concentrations, January and February, 1975 50

7. Ionic Analyses of Ground Waters at Two Locations in the Gravel-Cobble Aquifer and at One Location North of the Aquifer: Averaged Concentrations 51

8. Average Salt Concentrations for Sources of Surface and Subsurface Irrigation Return Flows and Weighted Estimates of Average Rates of Pickup 53

9. Estimated Annual Direct Income, Crop Substitution and Salinity Effects of Limiting Irrigation Water Delivered to Farms 55

10. Estimated Annual Costs for Reducing On-Farm Conveyance System Seepage with Aluminum Pipe in the Grand Valley 59

11. Community Income Reduction Under Two Options for Retiring Irrigated Land in the Grand Valley Trade Area 73

12. Summary of Annual Regional Costs and Cost Effectiveness: Upper and Lower Bound Estimates for the Land Retirement Options 75

13. Estimated Incremental Costs of Salt Removal for Proposed Alternative Control Measures, Grand Valley, Colorado (1975 dollars) 78

List of Tables, continued

TABLE PAGE

14. Mean Salt Loads, Stream Flows, and TDS Concentrations in the Study Reach: A Comparison of Three Time Intervals . . 98

15. Spring and Fall Precipitation and Runoff at Badger Wash, 1951-1972 100

16. Means, Standard Deviations and Coefficients of Variation of the Regression Variables: Annual Data, 1951-1972 114

17. Correlation Matrix of Selected Variables Used in Regression: Annual Data 120

18. Summary of Regression Results Relating Net Salt Pickup to Natural Causes: Annual Data 122

19. Summary of Regression Results Relating Net Salt Pickup to Selected Measures of Irrigation Variables: Annual Data . . 125

20. Summary of Regressions Results Combining the Natural and Manmade Causes: Annual Data 127

21. Coefficients of Variation for Selected Regression Variables: Monthly Data 133

22. Correlation Coefficients Between the Regression Variables and Net Salt Pickup: Monthly Data 135

23. Correlation Coefficients Relating the Influence of Time-Lags in Subsurface Irrigation Return Flows on Salt Pickup: Monthly Data 136

24. Summary of the Monthly Regression Analyses: Regression Coefficients and Tests of Significance 138

25. Means, Standard Deviations and Coefficients of Variation for the Quarterly Data 140

26. Summary of the Quarterly Correlation-Regression Results and Tests of Significance 142

27. Empirical Estimates of Rates of Pickup and the Magnitude of Total Salt Contributions from Natural and Manmade Sources . . 147

ACKNOWLEDGMENTS

We are grateful to Dr. William Franklin, Department of Agronomy (Colorado State University), William McClennagan, Bureau of Reclamation (Grand Junction), and Dr. Wynn Walker, Department of Agricultural Engineering, for their assistance in modeling agronomic and physical relationships; to William Klapwyk, manager of the Grand Valley Water Users Association, for his advice and assistance in data collection; to Charles Palmer, U.S. Forest Service (Denver), for his help with the input-output model; and to Roxanna Leathers, graduate student, Department of Economics (Colorado State University), for her assistance with the statistical analysis.

We also wish to acknowledge a number of our colleagues and professional associates at Colorado State University who have raised questions and provided useful criticism along the way: Drs. Gordon Kruse and Sterling Olsen (Agricultural Research Service, USDA), Dr. Norman Evans (Environmental Resources Center), Dr. Raymond Anderson (Economic Research Service, USDA), Professor Henry P. Caulfield, Department of Political Science, and Drs. Lee Gray, Anthony Prato, Lawrence Mack, and Paul Huszar of the Department of Economics.

The authors would also like to thank Mrs. Denese Gekas, Mrs. Electa Cameron, and Miss Elizabeth Young, for typing the drafts of this report.

Finally, the advice and patience of George Collins, Project Officer, have been greatly appreciated.

CONCLUSIONS

Several policy instruments can be identified by which public agencies might regulate saline irrigation return flows. These include direct effluent standards, taxes on effluent, public subsidy of private sector abatement activities, marketable effluent rights and direct public investment in abatement facilities. In the study area, salinity is produced by several hundred independent commercial farms. In such a case, the monitoring and enforcement costs of direct approaches appear likely to be exceedingly large. The analysis reported here assumes that the policy instruments would be indirect ones, which regulate use of resources used in the production process from which pollution emanates (i.e., water and land).

On the basis of certain plausible assumptions with respect to the proportion of applied irrigation water reaching the saline aquifer, a physical-economic model was developed to measure costs of reducing saline irrigation return flows. It was found that substantial reductions in on-farm drainage and in associated salt pickup could be achieved at relatively low cost (less than $3.00 per ton of salt removed).

Salt pickup associated with on-farm water conveyance systems is somewhat more costly to avoid. Aluminum pipe to replace on-farm laterals and head ditches can achieve salt reduction at about $8.00 per ton.

A more drastic approach would be permanent withdrawal of water supplies and the associated lands from crop production. Allowing for indirect as well as direct effects leads to an estimate of between $20 and $26 per ton of salt removed. (The preceding is a pure economic efficiency measure, and does not include the considerable social and political disruptions which would be the consequence of removing a substantial portion of the economics base of the region.) The estimated cost of the proposed structural measures being planned under the Colorade River Salinity Control Program is similar in magnitude, in excess of $20 per ton of salt removed.

Although conceptual disagreements regarding measures of downstream salinity abatement benefits are not resolved, the writers judge that such benefits are not large enough to warrant undertaking of any of the proposals other than adjustments in on-farm water management. Even this step is questionable, since the analysis presented here omits consideration of administrative and enforcement costs. Further, the burden of such programs would fall almost entirely on irrigation water users, although the efficacy of the programs is not fully proven.

A statistical analysis was performed to help clarify the origins of salt loading in the study area. Correlation and regression techniques were applied to annual, quarterly and monthly observations on salt pickup and natural phenomena (river flows, rainfall) and irrigation-related variables (diversions, estimated seepage, etc.). The analysis suggests that irrigation water diversions are considerably less important as a source of salinity than has been previously assumed by the federal agencies responsible for water quality monitoring and control. If the statistical analysis is confirmed by further investigations, rather large increases in the estimated cost per unit of salt removed (including the estimates reported here) are implied.

RECOMMENDATIONS

1. The salinity control programs authorized in PL 93-320, title II, for the Grand Valley should be postponed until uncertainties as to amount and source of irrigation return flow salinity are more clearly resolved.

2. Further analysis to determine the source and magnitude of salt pickup in the Grand Valley and elsewhere in the Upper Colorado Basin should be undertaken at once. Such investigations should include a more detailed and rigorous analysis of water quality and quantity data, a review and interpretation of completed and ongoing research by geologists, hydrologists and soil chemists and continued experimental programs.

Section I

INTRODUCTION

A. BACKGROUND

Managers of irrigated land in nearly all arid and semi-arid areas of the world face problems in coping with salinity (dissolved solids) in irrigation water [Moore, 1972]. Some dissolved solids are contained in river waters from natural leaching of rocks and soils or from inflows of saline water from underground sources. Examples of such contribution include return flows from irrigation, urban or industrial withdrawals which have picked up salts in addition to concentrating the salt load already present, and concentration due to evaporation from storage reservoirs.

Detrimental impacts are typically felt by water users from increasing concentrations of dissolved solids. Such detriments include decreased productivity and/or increased production costs for both agricultural and industrial water users, and in household uses, lower palatability of drinking water, reduced life of water pipes and appliances, and at higher concentrations of some elements, adverse health effects.

Salinity in the Colorado River Basin.- The Colorado River Basin in the southwestern United States presents a well-known example of the effects of salinity on economic activity. The modification of the river's flows has yielded benefits in the form of flood control, irrigation, electric power, recreation and municipal and industrial water supply. However, the River picks up a relatively high salt load from natural sources, and man's activities have served to further add to the natural salt load, as well as to concentrate existing salts. The Lower Basin states, especially California and Arizona, are the major withdrawers of Colorado River water and are experiencing increasing difficulty with rising salinity. The tail waters from the Colorado flow into Mexico. Farmers in that nation also use the Colorado for irrigation and the Mexican government has been quite critical of the quality of waters released from the United States [Oyarzabal, 1976].

The Colorado River passes through seven states on the way from its headwaters in the Colorado and Wyoming Rockies to its mouth in the Gulf of California (in Mexico). The states of the Colorado River Basin (CRB) include Wyoming, Utah and Colorado in the Upper Basin and Arizona, New Mexico, Nevada, and California in the Lower Basin. The River's salinity content ranges from an average of 50 parts per million (ppm) at its source to over 800 parts per million at Imperial Dam, Arizona, the last major U.S. diversion point before the water reaches Mexico. The salt load passing Lee Ferry, Arizona, the boundary between the Upper and Lower Basins, between 1941 and 1966 averaged 8.2 million tons per year. As of 1970, the annual salt load at Lee Ferry was around 8.5 million tons.

Sources.- The principal dissolved constituents in Colorado River water are the cations calcium, magnesium and sodium and the anions sulfate, chloride and bicarbonate. The presence of these, and of small amounts of other dissolved constituents, are commonly referred to as salinity. Increasing concentrations of these dissolved mineral salts threaten to become a major economic problem for users of Colorado River water.

Salinity increases result from two processes: salt loading and salt concentrating. Salt loading increases the amount of salt for a given amount of water and salt concentrating decreases the amount of water for a given amount of salt. Salt loading is the addition to the river system of mineral salts through natural and man-made sources. Salt concentrating is the rise in salinity through stream-flow depletions which concentrate the salt burden in the river system into a lesser volume of water.

Natural salinity sources contributing to salt loading may be further subdivided into point sources, such as springs and wells, and diffuse sources, such as high-salinity streams, percolation through highly saline soils, and surface runoff from precipitation. Man-made sources include return flows from irrigated lands and waste discharges from municipal and industrial sources.

Effects.- The amount of salt in water directly influences the utility of the water. Thus salinity levels greatly affect the types and amount of water use. The extent of this relationship will become apparent after an examination of the water uses in the Colorado River Basin.

Water uses are of two general types--withdrawal and instream uses. Withdrawal uses involve removal of the water from the river system and include irrigation, stock watering and municipal and industrial uses. Instream (in situ) uses include power generation, water recreation, navigation, groundwater recharge, fish and wildlife habitat, silt control, and water quality control.

Increases in salinity tend to raise costs of industrial water users by increasing treatment, conditioning, and/or operating and maintenance costs. For example, salinity can cause excessive water hardness and speed corrosion of recirculating systems, resulting in higher costs for industrial use. Too much salinity affects domestic users by affecting water taste, hampering gardening, raising water softening costs, and speeding pipeline corrosion. In addition, salinity shortens fabric life and increases the consumption of detergents and soaps by domestic users. Salinity may also affect the type and quantity of fish and other aquatic life and thus adversely affects recreational values.

Increasing salinity in irrigation water imposes additional costs on irrigators. The amount of extra water needed for leaching out salts in the root zone rises with increased salinity of the applied irrigation water. When extra water is not available, the producer is left with the choice of suffering a drop in yield, retiring some of his land in production to gain the extra water, or changing to more salt-tolerant, but typically, less profitable crops. More expensive production practices may also be required to assist in germination or to drain off excess waters.

Salinity concentrations in the Upper Basin are not expected to adversely affect agricultural crops in that Region in the foreseeable future, except in poor drainage areas, such as those along the river in Grand Valley. In the Lower Basin salinity concentrations are now approaching critical levels because the types of crop grown in the Lower Region are generally those which are more susceptible to salinity damage. The U.S.

Environmental Protection Agency has recently calculated potential damage from salinity in the Colorado River Drainage Basin. Total penalty costs, defined as total marginal costs of increases in salinity concentrations above 1960 base conditions, are the sum of direct penalty costs incurred by water users and indirect penalty costs imposed on the economy of the Region. For the Lower Basin and Southern California Service Area, total penalty costs were projected to reach $25.4 million annually (in 1960 dollars) by 2010. Irrigated agriculture would account for $21.3 million of this total. The Southern California Service Area would incur over 75 percent of the total $25.4 million penalty costs. (For an explanation of how these estimates were calculated, see U.S. Environmental Protection Agency, "The Mineral Quality Problem in the Colorado River Basin," Appendices B and C [1971].)

Potential Means of Alleviation

There are numerous technically feasible salinity management programs for the Colorado River Basin [U.S. Bureau of Reclamation, 1972]. However, legal and institutional constraints and economic feasibility tend to place limits on the practicality of many programs. Salinity control measures resolve into two basic types: measures to augment flow and measures to reduce salt input. Possible augmentation methods include: (1) importation of high-quality water, (2) weather modification to increase precipitation of low-saline waters, (3) utilization of water produced from geothermal energy resources, and (4) conservation of water by reducing non-beneficial evapotranspiration through: phreatophyte control, surface evaporation control, increasing efficiency to farm use, decreasing irrigated acreages, and control of future development. Salt load reduction may take place by: (1) impoundment and evaporation of major salt-contributing springs, wells, and other point sources; (2) controlling salinity from irrigated lands by elimination of high salt-producing areas from crop production, decreasing quantities of saline return flows, avoiding contact between discharges and heavy salt-producing areas, exporting or evaporating high salinity return flows, reducing groundwater pumpage of high salinity water, or reducing seepage losses from conveyance facilities; (3) discharging high-salinity municipal and industrial wastes into evaporation ponds; and (4) constructing and operating desalinization plants where feasible.

Examples of salinity management and control practices in an agricultural area would be: irrigation scheduling or regulation of irrigation frequencies, amounts, and methods; land preparation to promote efficient surface irrigation practices; effective drainage practices; lining of canals and conveyance systems; and perhaps the most drastic solution, retirement of land from agricultural production.

The multiplicity of sources of salinity, the variety of potential means for their abatement and the fact that the receptors of damage from salinity pollution are located in different political jurisdictions than the principal sources of pollution, implies that region-wide management practices must be adopted.

B. OBJECTIVE AND PLAN OF STUDY

The primary objective of this study is to develop and apply a procedure for analyzing the economic consequences of implementing alternative technologies and institutional arrangements designed to control salinity from irrigated agriculture. The Grand Valley, located on the Colorado River near Grand Junction, Colorado, is selected as the case study area.

Specific objectives are:

1. To identify alternative structural and nonstructural control mechanisms which can influence stream salinity levels associated with irrigated agriculture.
2. To estimate and evaluate the direct costs of technically feasible measures designed for on-farm salinity control.
3. To estimate the direct and indirect economic impacts of selected salinity control policies on the local economy.

A second major objective, which was undertaken late in the study, is to statistically test competing hypotheses regarding the magnitudes of salt pickup from irrigation as compared with natural causes in the study area.

C. ORDER OF PRESENTATION

The balance of the report is organized into six sections. In section II a brief description of the Grand Valley and justification for using this area as a case study is given. We outline our theoretical framework and analytical procedures in section III. The empirical analyses are presented more or less in the order that they were performed: on-farm water management (section IV), land retirement (section V), and statistical analysis of salinity mechanisms (section VI). The appendix contains the sources of literature consulted and supporting information.

SECTION II

THE GRAND VALLEY AS A CASE STUDY

A. OVERVIEW

The Grand Valley is located in west central Colorado at the confluence of the Gunnison and Colorado rivers in Mesa County (Figure 1). Paralleling the Colorado River for about 30 miles, the Valley averages seven miles in width and about 4400 feet in elevation. Summer weather is characteristically hot and dry and the winters cold. Beginning in April, the normal frost-free season averages about 190 days. With an annual precipitation averaging 8 to 10 inches, irrigation is necessary to maintain a viable commercial agriculture in the Valley.

Grand Junction, with a population of about 25,000, is the principal commercial center in the Valley, and in Colorado's western slope. Agriculture is an important source of employment and income to a local population of about 60,000 people in Mesa County. However, in recent years basic manufacturing and service industries have become the mainstay for an otherwise traditional agricultural community. Approximately 56,000 acres of land are presently cultivated out of a total arable area exceeding 100,000 acres. Urban and industrial expansion, service roads and farmsteads, and idle and abandoned lands account for most of the balance not farmed [Walker and Skogerboe, 1971].

The diversified agricultural industry in the Valley is comprised of both livestock and crop production activities. Major crops grown

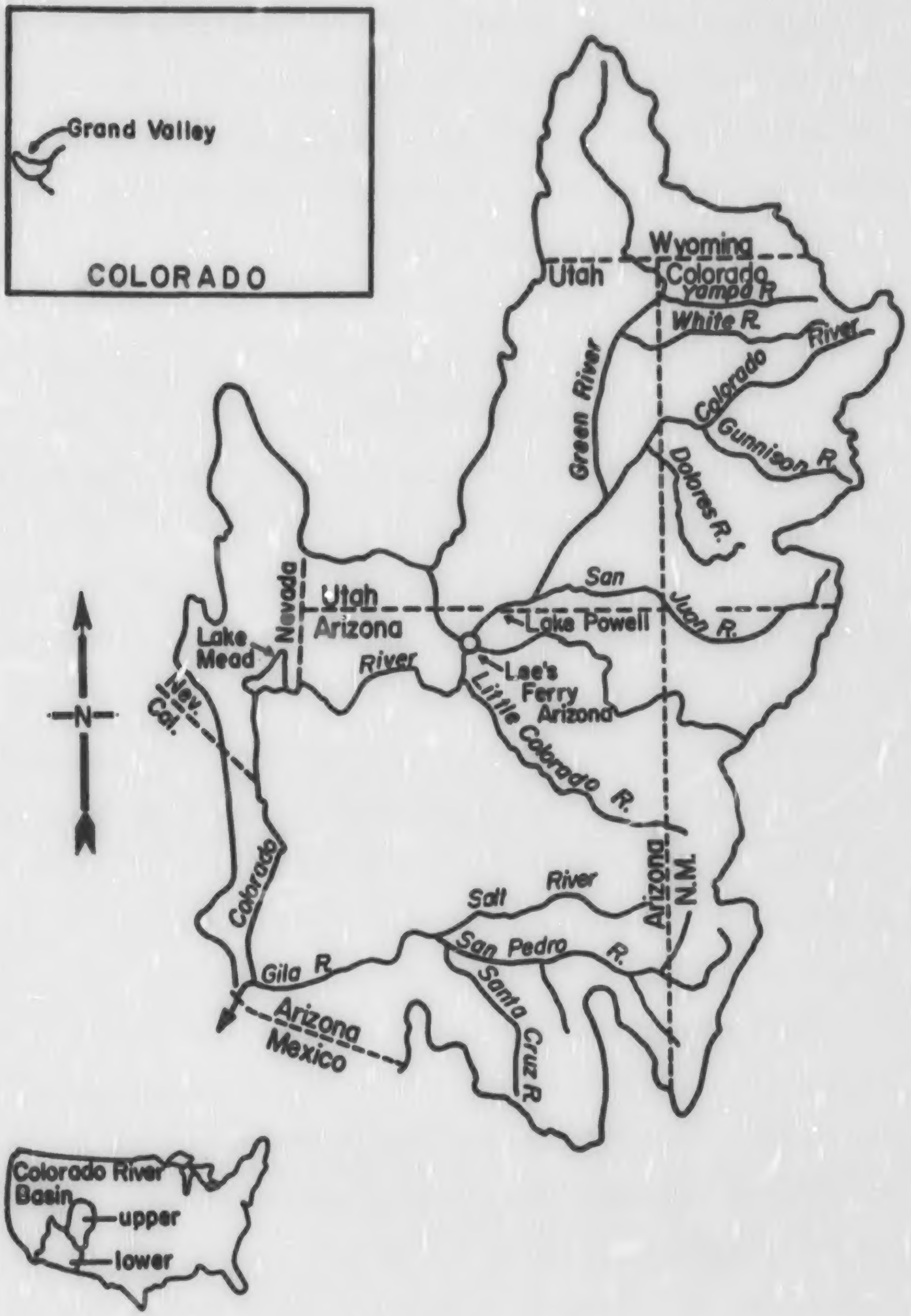

Grand Valley
COLORADO
Wyoming
Utah
Colorado
Yampa R.
White R.
Colorado
River
Green River
Gunnison R.
Dolores R.
Nevada
Utah
Arizona
San
Juan R.
Lake Powell
Lake Mead
River
Lee's Ferry Arizona
Nev.
Cal.
N
Little Colorado R.
Colorado
Salt
River
Arizona
N.M.
San Pedro R.
Gila R.
Santa Cruz R.
Arizona
Mexico
Colorado River Basin
upper
lower

Figure 1. The Colorado River Basin

include corn, alfalfa, sugar beets, small grains and permanent pasture. Slightly less than ten percent of the irrigated acreage is planted to pome and deciduous orchards. Small acreages of vegetables and other specialty crops such as turf grass are also grown in the area. The Grand Valley has long been favored wintering area for cattle and sheep grazed on high summer ranges to the east and south.

B. IRRIGATED AGRICULTURE

Following settlement in the early 1880's, irrigation companies were organized to divert water for agricultural use. Many of the original companies have since been consolidated, leaving five which presently supply all the water diverted under original decrees: The Grand Valley Irrigation Company (1882), the Grand Valley Water Users Association, using water developed by the U.S. Bureau of Reclamation in 1916, the Palisade and Mesa County Irrigation Districts (1890's), and the Redlands Water and Power Company [Skogerboe and Walker, 1972]. Because irrigable acreages were typically overestimated within the newly-formed irrigation districts, and due partially to a gradual decline in irrigated acreage as a result of waterlogging, and more recently urbanization, Grand Valley farmers have always had an abundant supply of water.

Early evaluations of irrigation efficiency, which were initiated in response to immediate drainage problems in the lower-lying lands, documented Valley-wide efficiencies of 30 to 40 percent [U.S.D.A. and Colorado Agricultural Experiment Station, 1957, and Decker, 1951]. However, the threat of rising water tables and salinity problems encountered on waterlogged soils was not enough incentive to offset wasteful use of very low-cost project water. Average charges in 1975 were less than two dollars per acre foot. Average river diversions sometimes exceed 600,000 acre feet annually, but only 175,000 acre feet are required to meet normal crop consumptive use [Skogerboe et al., 1974].

Soils vary throughout the Valley in surface textures ranging from loam to fine silty clay but share a common parent material derived from Mancose shale [Soil Conservation Service, 1955]. Being low in organic matter, these soils are prone to nutrient leaching (especially nitrates) and have restricted internal drainage at lower elevations. The prevailing topographical slope of the Grand Valley ranges between 50 and 80 feet per mile, which effectively limits irrigation methods to furrow and corrugation techniques [Bishop et al., 1967].

C. RETURN FLOW SALINITY

U.S. Bureau of Reclamation [1974] analyses of river waters entering and leaving a reach of the river which includes the Grand Valley indicate that salt pickup on the average amounts to approximately 600,000 tons per year. This reach, determined by the location of U.S. Geological Survey sampling stations at Cameo, Colorado and Cisco, Utah, on the Colorado River, and at Grand Junction, Colorado on the Gunnison River, includes a surface area of about 3,000 square miles of which less than four percent are irrigated lands. Nonetheless, it has been concluded that the overwhelming proportion of salt pickup (93 percent) in this reach results from irrigation activities [Environmental Protection Agency, 1971].

Salt pickup as related to agricultural activity is defined as an increase in the total salt load of water leaving an area after being diverted for irrigation compared to the salt load of the water entering the area. The present analysis is based on an estimate of 460,000 tons (per average year) of salt pickup attributable to irrigated agriculture or over 8 tons per irrigated acre. An additional 140,000 tons is thought to be contributed by natural sources such as surface runoff from surrounding desert in the study reach.

Salt Pickup Mechanisms

Several physical explanations have been proposed to account for the above pickup, but agreement concerning the relative importance of any specific pickup mechanisms is lacking at the present time. Three basic types of pickup mechanisms considered in this report are: (1) irrigation waters which dissolve and transport salts fron subsurface sources, (2) irrigation waters which dissolve and transport surface salts, and (3) salts added to streams or water courses by surface runoff of precipitation and snowmelt.

The salt ion composition of most streams and rivers is closely related to the geology of the watershed and the makeup of watercourses in areas undisturbed by man. Diversion and use by man can impose marked changes in water quality from that found under undisturbed conditions. An understanding of the geology in the Grand Valley and surrounding area is especially important with regard to salinity control and implementation of specific control measures for irrigated agriculture.

Geological formations on the southern edge of the Grand Valley, the Morrison, Summerville, Entrada, Kayenta, and Chinle, in descending order, overlie granite, gneiss, and amphibolite at the Uncompahgre uplift (Figure 2). On the east and to the north of the Valley later geologic formations

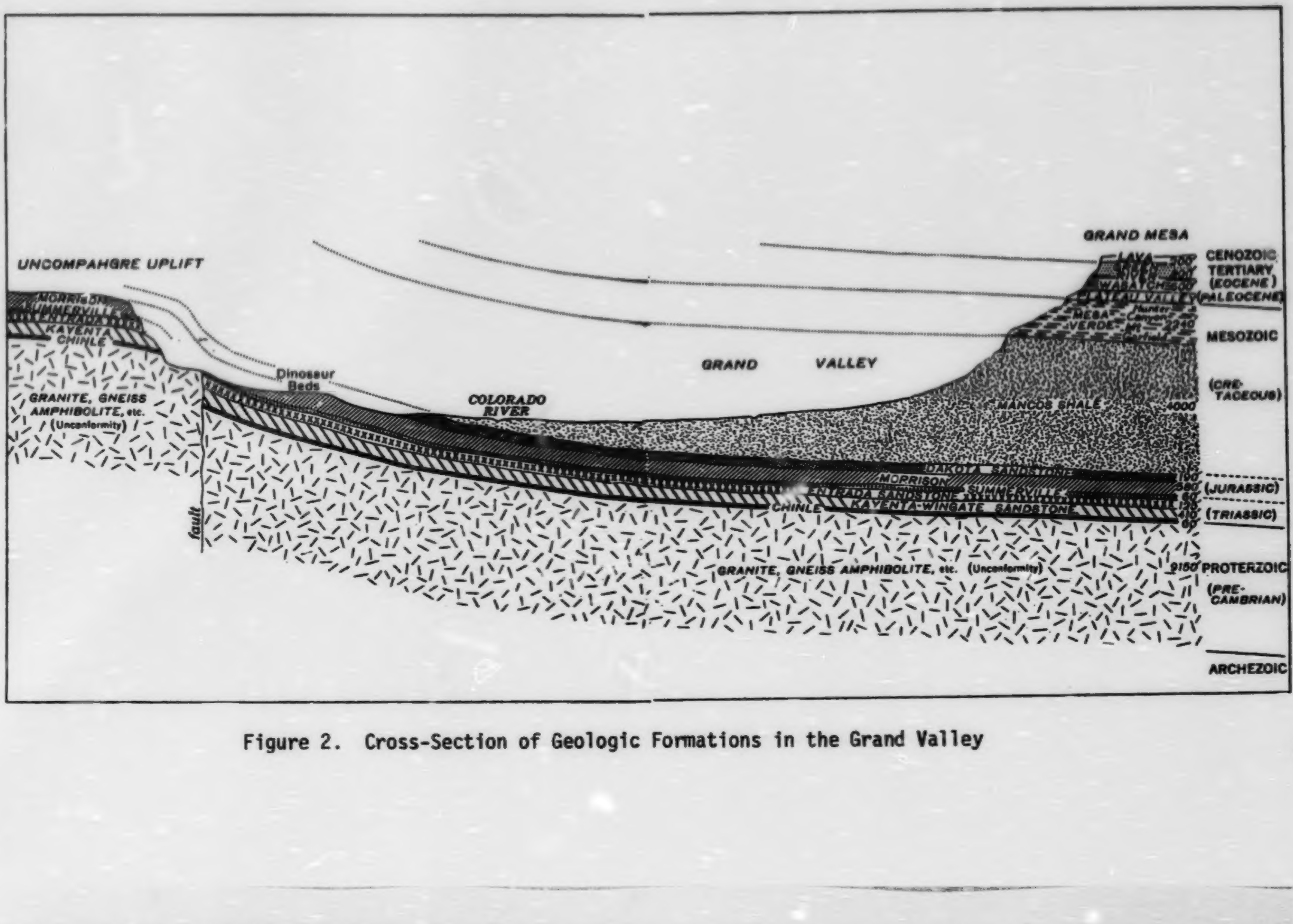

UNCOMPAHGRE UPLIFT
MORRISON
SUMMERVILLE
ENTRADA
KAYENTA
CHINLE
GRANITE, GNEISS AMPHIBOLITE, etc. (Unconformity)
fault
Dinosaur Beds
COLORADO RIVER
GRAND VALLEY
GRAND MESA
LAVA
WASATCH
PLATEAU VALLEY
MESA VERDE
MANCOS SHALE
4000
DAKOTA SANDSTONE
MORRISON
ENTRADA SANDSTONE
SUMMERVILLE
CHINLE
KAYENTA-WINGATE SANDSTONE
GRANITE, GNEISS AMPHIBOLITE, etc. (Unconformity)
2240
9150
CENOZOIC
TERTIARY
(EOCENE)
(PALEOCENE)
MESOZOIC
(CRE-TACEOUS)
(JURASSIC)
(TRIASSIC)
PROTERZOIC
(PRE-CAMBRIAN)
ARCHEZOIC

Figure 2. Cross-Section of Geologic Formations in the Grand Valley

are exposed. In descending stratigraphic order, these formations are basaltic lava, Green River Wasatch, Plateau Valley, Mesaverde, and the marine-deposited Mancos shale overlying the formations named above [Knobel et al., 1955]. The Mancos and Wasatch formations typically contain large quantities of fossil salts. Mancos Shale is the dominant formation in the Grand Valley itself, underlying 80 to 90 percent of the area.

The Valley soils were formed residually from the Mancos Shale and from alluvial materials deposited by the Colorado and Gunnison Rivers. The alluvium covers thick beds of porous gravelly and cobbly sand (the ancient river course) that extend from east of Grand Junction at the head of the Valley to Fruita. The northern edge of the aquifer, depicted in Figure 3, roughly parallels the Grand Valley Canal and underlies nearly half of the Valley's irrigated acreage. This gravel-cobble layer conducts water rapidly and a high water table occurs in the general area contiguous to the River.

The primary cause of return flow salinity is thought to be the extremely saline aquifers (as high as 10,000 ppm) overlying the marine-deposited Mancos Shale formation. Lenses of salt contained in the shale are dissolved by water entering and coming into chemical equilibrium with this formation before returning to the river channel. Seepage from unlined canals and laterals flowing into and through the gypsiferous and saline alluvium and Mancos Shale substrata has been cited as the primary pickup mechanism. On the basis of canal seepage measurements, Kruse et al. [1975] reported that canal and lateral seepage alone could possibly

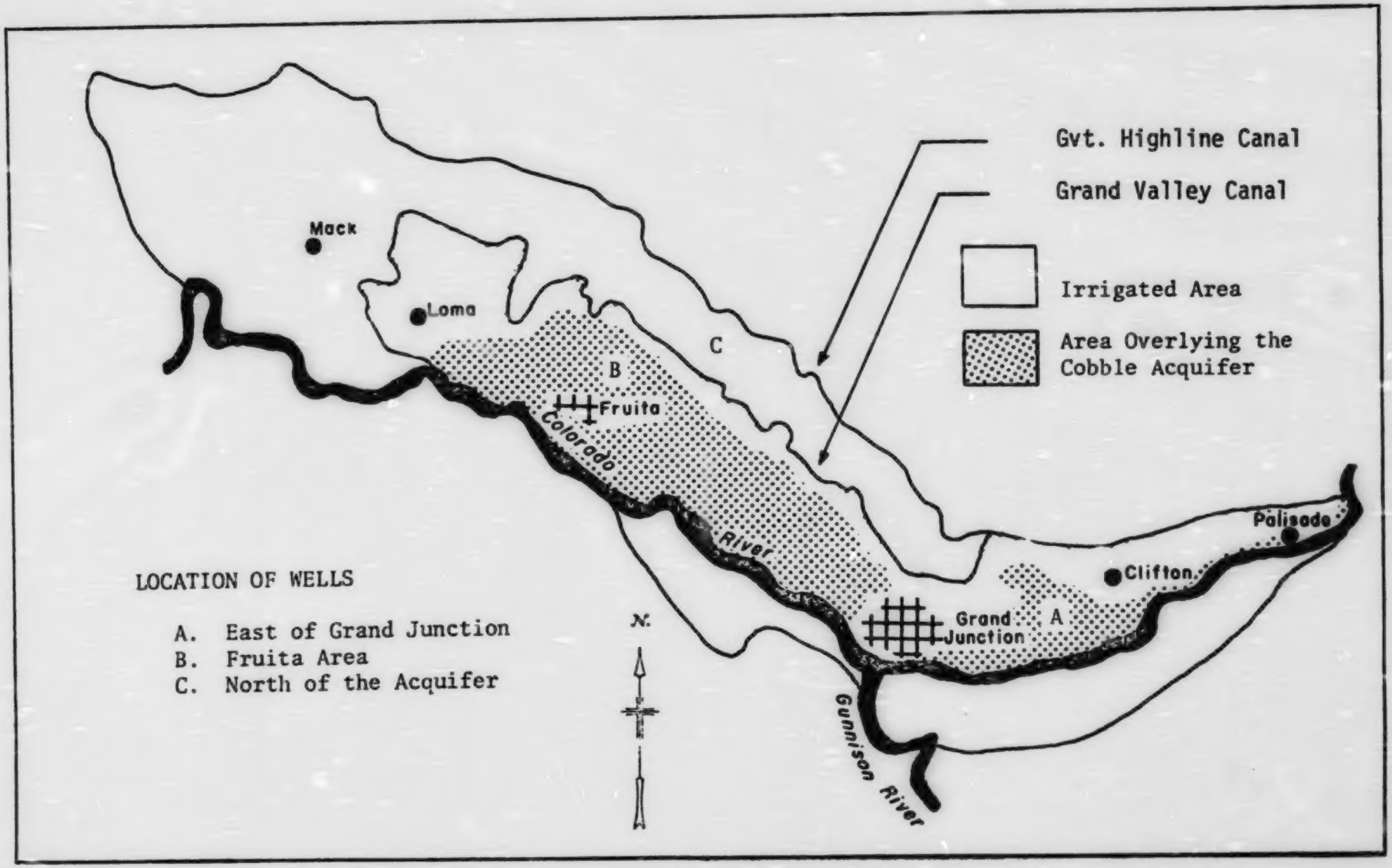

Gvt. Highline Canal
Grand Valley Canal
Irrigated Area
Area Overlying the Cobble Acquifer
Mack
Loma
B
C
Fruita
Colorado
River
Grand Junction
A
Clifton
Palisade
Gunnison River
N.
LOCATION OF WELLS
A. East of Grand Junction
B. Fruita Area
C. North of the Acquifer

Figure 3. The Grand Valley of Colorado

account for total annual salt pickup. Over-irrigation and excessive deep percolation losses through saline and gypsiferous substrata have also been cited as a major salt pickup mechanism in conjunction with seepage [Skogerboe _et_. _al_., 1974a and 1974b]. Skogerboe and others estimate that about 45 percent of the total annual pickup is a result of deep percolating water due to inefficient irrigation practices.

Another pickup mechanism possibly involved is the dissolution of salt on soil surfaces in surface runoff water. Runoff containing suspended solids from salt-bearing soils could result in salt pickup if erosive furrow or rill irrigation took place. Since the majority of the land is irrigated by rill or furrow methods in the Grand Valley, it is possible that this pickup mechanism could be important. Although few studies of this phenomenon have been undertaken, the available evidence suggests that the quality of water leaving irrigated fields is about the same as the river water at the point of diversion [Robinson and Franklin, 1973]. Initial increases in ion concentrations found in the first few hours of irrigation during the early part of the season were not considered to present a significant change in overall water quality.

A third salt pickup mechanism, not related to agriculture but difficult to separate from irrigation effects is the dissolved salt contained in natural runoff from rainfall and snowmelt. Since unmeasured subsurface drainage water and surface runoff water from precipitation both flow into the natural drainage ways and washes, it is difficult to assess the importance of salt pickup resulting from precipitation in and around the irrigated area.

Proposed Control Measures

Until the initiation of the present study, research concentrated on various structural control technologies including lining of conveyance systems and on-farm drainage improvements. Although a program of scientific irrigation scheduling designed to improve on-farm water management has been under study since 1972, feasibility analyses have been limited to a few selected farms with no detailed Valley-wide evaluations being attempted. Other nonstructural control possibilities have had little serious consideration.

A number of procedures for reducing salt loading in the Grand Valley are under consideration by the U.S. Bureau of Reclamation [1976], the federal agency responsible for implementing the Basin-wide salinity control program [Public Law, 93-320, Title II]. One plan calls for the lining of all main canals and laterals to prevent seepage. The published estimates indicated an investment requirement of about $90 million to line 715 miles of canals and laterals. This proposal is expected to reduce salt pickup by about 200,000 tons per year.

Several lengths of canals and laterals have been lined since 1970 in a demonstration area on the east side of the Valley [Skogerboe and Walker, 1972]. These researchers estimate that 70 to 80 percent of total seepage losses could be prevented by lining all canals and laterals (including on-farm delivery ditches). However, the costs of such a program appear to be quite high. Amortizing the investment over thirty years at six percent yields an annual cost of $6.54 million, equivalent to $32.72 per ton of salt removed.

Inefficiency in on-farm water use, stemming from a combination of abundant supply, low user costs, and problematic soil-topographic characteristics, has encouraged interest in irrigation scheduling as a Basin-wide possibility for salinity control. The results of irrigation scheduling are presently inconclusive, but the program holds much promise as a low-cost control measure [Skogerboe and Walker, 1973; and Anderson et al., 1974]. Improved on-farm efficiencies may possibly have local benefits, including increased yields and additional productivity on previously waterlogged soils, in addition to reduction in downstream damages.

Research on the use of drainage technologies has emphasized interception of deep percolating water below the root zone before it has reached chemical equilibrium in the saline aquifers. Because the deep, open ditch-type drains in use since the early 1920's are largely ineffective for this purpose, a drainage program would also have to include extensive renovation of existing structures to be effective. Costs of field drainage and renovation also appear to be quite high, and resulting water quality improvement uncertain. Additionally, drainage improvements without improving on-farm water use efficiency would possibly make matters worse than they are [Skogerboe et al., 1974b].

Another option, currently under study by Walker [1976], involves desalting highly saline aquifer and return flow waters which would be intercepted before entering the river. Although expensive, this procedure is perhaps the only sure way (other than land retirement) that significant amounts of salts can be removed from drainage waters.

D. JUSTIFICATION

The Grand Valley is an interesting and challenging area to physical and social scientists alike for investigating salinity abatement measures for future implementation in the Valley and elsewhere. Because Mancos shale is so widely distributed in the upper drainage of the Colorado River Basin, the likelihood of other irrigated localities confronting similar water quality situations suffices to justify extensive research in the Grand Valley for immediate applications in other areas. Constraining factors have been encountered at all levels of study: in modeling physical and hydrosalinity relationships, institutional inflexibilities governing private water use and ownership, and identification of socioeconomic consequences for communities directly and indirectly affected.

Degraded irrigation return flows, by way of seepage and deep percolation through saline soils and underlying geologic formations which return increased salt loads to the river system, make the Grand Valley one of the most significant man-made sources in the entire river basin.

However, estimates of the specific mechanisms and sources of salt pickup remain to be established. The various academic and federal agency teams studying the problem have proposed conflicting estimates of the proportion of salt pickup in the study area due to natural vs. man-made causes, and within the man-made category, the proportions due to seepage from respectively, (a) the main canal system, (b) the on-farm distribution systems, and (c) the fields themselves. Since the appropriate control program may differ among these sources, it is important that these relationships be well understood. The estimates used in our analysis represent a compromise among the competing hypotheses and might not be endorsed by any of the research groups.

SECTION III

RESEARCH PROCEDURES: CONCEPTS, METHODS AND ASSUMPTIONS

A. INTRODUCTION

A complete economic analysis of a proposed pollution control policy will attempt to measure (a) the benefits of pollution control (in terms of willingness of receptors to pay to avoid the damages), (b) costs of reducing or removing waste discharge, (c) the costs of monitoring and enforcement of regulations, and (d) where relevant, indirect or secondary costs and benefits. A feasible policy is one which the incremental benefits exceed the incremental costs [Kneese and Schultze, 1975]. Further, the implications of proposed cost sharing or pricing arrangements should be established.

Several policy instruments by which public agencies might regulate salinity discharge can be identified. These include direct effluent standards, taxes on effluent, public subsidy of private sector abatement activities, marketable effluent rights, direct public investment in abatement facilities, and indirect controls on use of resources complementary to the production process from which pollution emanates (i.e., water and land) [Peskin and Seskin, 1975].

Where salinity is produced by several hundred independent firms, as is the case in the Grand Valley, the monitoring and enforcement costs of most of the direct approaches (standards, taxes and effluent permits) appear likely to become exceedingly large. Other analyses have reported on costs of direct structural control methods [Skogerboe, et al., 1974; and Utah State University 1975]. Hence the approach followed in the studies reported here emphasizes indirect policy instruments which regulate water or land use in irrigated crop production.

B. HYPOTHESIZED MEANS OF REDUCING SALINITY

Control of water supply seems to be an obvious approach to reducing salinity in irrigation return flows. The prevailing water pricing procedures imply a negligible marginal price to the user and there is little concern for limiting diversions to the amount specified by the water right. Farmers now divert much in excess of even the most generous estimates of evapotranspiration, leaching and carriage requirements. These excess diversions lead, in turn, to potentially large deep percolation and seepage losses. Hence, it is hypothesized that on-farm sources of salt pickup could be reduced by constraining water supplies thus encouraging farmers to adopt more efficient irrigation practices.

On-Farm Control Options

Three hypothesized practices which influence deep percolation are examined in this study. The first has to do with modifying traditional irrigation practices. Irrigators may, given factors such as size of field, slope and row spacing, vary the rate of water applied per unit area in the crop season by changing (a) the length of time water is allowed to run in each furrow, (b) the size or number of siphon tubes (so that the rate of application is changed), and/or (c) the interval between irrigations. Previous research by agricultural engineers has revealed that soil infiltration rates in the study area change dramatically as the irrigation season progresses [Gilley, 1968; Skogerboe, 1973]. Early in the year, when soils are loose and open following pre-plant tillage operations, they permit rapid infiltration of water. During this time, relatively large amounts of water can percolate below the root zone if excess water is applied. This may occur when irrigation water is allowed to run at a slow rate for long periods to achieve adequate wetting in the lower end of fields. Later in the year, the soil tightens up and the potential for deep percolation is reduced.

It has been proposed that a relatively simple adjustment of irrigation practices, namely, increasing the rate of discharge but reducing the amount of time that water flows in each furrow, could still achieve uniform wetting while effectively reducing deep percolation [Kruse, 1975]. This adjustment would be required only during the first two irrigations of the season, since lower infiltration rates and higher evapotranspiration losses during the hotter summer period lead to conditions where significant deep percolation would not be experienced even with longer sets.

A second on-farm management practice which could affect rates of deep percolation is adjustment in cropping patterns. Since irrigation crops typically vary as to planting dates, length of growing season and evapotranspiration requirements, deep percolation is crop-specific. A reduction in deep percolation per unit area could be achieved by substituting crops which are low contributors for those which are more of a problem.

The third approach is to control seepage loss in the farm delivery system. Most present conveyance laterals and head ditches in the Grand Valley are unlined. By converting the on-farm conveyance system of unlined ditches to solid, moveable aluminum pipe, as much as 95 percent of on-farm seepage losses might be saved and used for irrigation. Replacing head ditches with gated aluminum pipe may also improve the uniformity of water application (hence reduce deep percolation), but no such empirical evidence is available to document this for Grant Valley conditions.

Land Retirement

A more drastic approach to control of saline return flows in an irrigated area would be permanent withdrawal of water supplies [Howe and Orr, 1974]. Because of the aridity of the study area, this would imply the irrigated lands would be permanently retired from crop production. Land retirement, either compulsory or non-compulsory, is a zero discharge control option that could be implemented in conjunction with other less costly structural and non-structural control measures.

Water supplies could be withdrawn in two ways. First, the least productive soils could be taken out of production on a selective basis. This option would have a minimum impact on the local economy, but would not necessarily be less expensive in comparison to a second option, namely retirement of an entire block of irrigated land and service canals and laterals. This alternative could have a greater impact on the local economy, since the soils included would have a higher average productivity. However, because seepage losses would be omitted under the selective (or partial) retirement scheme, the amount of salts avoided per acre or unit area would be considerably larger with the complete retirement option.

C. CONCEPTUAL FRAMEWORK FOR ESTIMATING PROGRAM COSTS

Conventional theory of the firm and interindustry analysis comprise the formal analytical approach and subsequent empirical analyses reported in this study. The technique of linear programming is used to derive the cost-effectiveness of on-farm controls programs. Indirect impacts associated with land retirement are assessed using a small region input-output model of the impacted area.

Representative Farms and Linear Programming

Linear programming models of five representative farm situations (each characterizing a different farm size category) provide the basis for deriving estimates of the direct economic costs of on-farm salinity controls. This approach is based upon the presupposition that farmer resource allocation behavior can be appropriately represented in the activity analysis-optimization format [Day, 1963]. The linear programming algorithm utilized in the analysis solves a conventional short run land and water allocation problem, subject to constraints on cropland, water and acreages of specified crops. The objective function is net income (defined as gross crop sales minus operating costs). Aggregated, the models form a Valley-wide characterization of farm sizes, resource levels, production technologies, cropping patterns and irrigation practices. Under alternative price and operating assumptions, such models of representative farms have proven useful in assessing production response and decision behavior relating to a broad range of policy issues [Kelso, *et al.*, 1973].

Salinity levels are included in the model solutions via estimates of deep percolation. The estimates are derived from a separate soil-water-crop model which characterizes the hydro-salinity relationships for surface irrigation techniques in the Valley. Each crop production activity incorporates a coefficient representing annual deep percolation per acre. Our principal results assume that salt is picked up at the rate of five tons of dissolved solids per acre foot of deep percolating water.

This rate represents the average for the Valley and reflects a compromise among conflicting estimates. However, since this parameter is regarded as the least reliable in the analysis, we also consider alternative rates in evaluating the cost effectiveness of on-farm control programs.

The model is solved to find the net income-maximizing situation for each of a number of increasingly severe constraints on water supply. Direct costs are computed in terms of net income losses due to hypothesized imposition of water supply constraints. It is assumed that a farmer, facing a constrained water supply, would seek modified irrigation practices which would increase his efficiency of water use. Modifications in typical (current) irrigation practices are analyzed in the model by introducing production processes with varying water supplies, application rates, timing and methods.

Some of such practices would reduce deep percolation losses, hence salt pickup contributed by that source. Other modifications may involve substituting high water using crops for crops which require less water, or adopting seepage control measures on the farm.

Interindustry Analysis

The adverse effects of some types of salinity control programs, for instance land retirement, can be expected to involve indirect as well as direct costs. Indirect or secondary effects are defined as the consequences which stem from the original or direct effect. While small-region changes in income are not synonymous with changes in national income, a careful delineation of local consequences can be useful information for the public decision-making process.

Techniques of secondary impact analysis, made possible with the use of an input-output model of the U. S. economy, were formally introduced by Leontief in 1936. Since that time the input-output approach has become a popular tool for regional analysis. But like other useful analytical tools the technique has been misused in that it was often applied in a purely mechanical way [Richardson, 1972].

The indirect costs of land retirement are estimated using a small region input-output model of the Grand Valley economy. The approach followed in constructing and using the model draws upon some recent extensions of the technique suggested by Harmston and Lund [1967]. These economists have successfully applied the input-output framework to community (small) economic systems which, heretofore, have not received the careful attention of regional analysts. Other modifications in conventional methods are also used where deemed appropriate to the purposes of our analysis. These are discussed briefly in section V of this report, and in more detail in a supporting manuscript [Leathers, 1976a].

D. ECONOMIC BENEFITS OF REDUCED SALT DISCHARGE

We have not ourselves performed any studies of downstream benefits of salinity control programs, but as with the upstream control program costs, a number of questions of concept and method in the published estimates remain unresolved. Some of the more important of these are reviewed here. First, there is the question of secondary or indirect economic benefits. Most economists agree that secondary benefits are justified under a national accounting stance only if there can be identified a failure of market processes to adequately function in forward or backward-linked sectors. Typical example of such failures include resources which might become unemployed or immobile unless salinity levels are reduced. We cannot identify any such conditions which would warrant incorporating secondary impacts into the economic evaluation of salinity control. There undoubtedly would be pecuniary or regional income distribution effects. Some of these would be negative, e.g., the reduced income of household appliance and plumbing firms. Such losses would probably be offset by gains in the regional economic sectors which eventually profit by reduced consumer spending to mitigate salinity damage, but the net effect is unknown.

A second issue involves the locus on the aggregate damage function where marginal damages are computed. We disagree with the forecasts which project salinity in the Lower Colorado River Basin to increase in accordance with past trends. Since the damage function is non-linear, marginal damages computed on the basis of projected high salinity levels are much greater than estimates derived from current salinity levels. Due to the fact that most salinity is from natural causes and since man-made increments to salinity will be inhibited by environmental regulations, we believe damage estimates will be most accurately derived by use of roughly current levels of salinity.

A third issue rests on the need for employing the cost of the most likely alternative for dealing with salinity as a measure of downstream damages. Where damages can be feasibly mitigated at a cost less than the damages avoided, the benefits are not greater than the cost of the alternative process. The southern California area has recently acquired relatively large supplies of high quality Feather River water. Blending such water with Colorado River water, or replacing the latter outright, represents perhaps a less expensive alternative than continuing to suffer damages from more saline Colorado River supplies.

We interpret a report of the Environmental Protection Agency [1971] to imply that direct downstream benefits (updated for 1975 prices at current levels of salinity) are about $6 per ton of salt removed. At this level of benefit, it is clear that the more expensive structural control measures would not be economically justified. Further, the zero discharge called for in recent U. S. water quality legislation could only be achieved at economic costs several times larger than the downstream benefits, not to mention the significant social impacts on the local community due to an abrupt cessation of production in an important sector in the regional economy.

The Bureau of Reclamation [1976] has published an alternative estimate of direct downstream benefits which amounts to $17 per ton of salt removed. This estimate apparently does not consider the possibility of using Feather River water as an alternative source in southern California, and further, relies on higher projections of future salinity levels than we consider appropriate.

SECTION IV

THE ECONOMICS OF ON-FARM SALINITY CONTROL

A. INTRODUCTION

Management of irrigation water on the farm has received much attention as a potential salinity abatement strategy in the Upper Colorado River Basin. The attractiveness of on-farm controls stems from the belief that such measures represent the least-cost means of removing substantial quantities of salts while at the same time conserving irrigation water. However, the efficacy of this proposition has been only partially examined thus far using sound empirical data. This section reports the first such comprehensive study.

Our analysis focuses on three general managment options that farmers could adopt to reduce return flow salinity. These include: (1) improving irrigation application efficiency, and (2) crop substitution, both of which could limit salts picked up via deep percolation from irrigated fields; and (3) improving on-farm water handling with the use of aluminum pipe conveyance systems, thus limiting seepage-induced salt pick-up.

The analysis and results are presented in four parts. In part one, section B, we discuss the formulation of the representative farm models used to characterize farmer response behavior. The assumptions and informational requirements which underlie salinity response effects are reported in section C. In the last section, D, our major findings are reported. This section also includes a discussion of policy implications and limitations of the analysis.

B. SIMULATING FARMER RESPONSE

Linear programming models were developed to simulate aggregate (valley-wide) production response to various nonstructural salinity controls that farmers could implement themselves. A disincentive, in the form of a constraint on irrigation water supplied to farms, is presumed to provide the impetus for adoption of more efficient irrigation practices thus influencing salts picked up in excess drainage waters.

Data Source and Sampling Method

Data for this analysis were collected by the authors in connection with an earlier study. Personal interviews with farmers were conducted in the Grand Valley during the summers of 1972 and 1973. The participants were randomly selected from water user lists made available by the irrigation companies and associations which divert irrigation water from the Colorado and Gunnison rivers. These lists typically include numerous small users (one to three acres in size) as well as commercial farms. Individuals with less than a 40 acre water appropriation (about 1 cfs) were not included in the sampled population. Subsequently, from approximately 350 "commercial" farms (40 or more acres in size), 98 complete interviews were secured, a sampling rate of about 28 percent.

The interview schedule was designed to obtain a wide array of information: the numbers and sizes of farms; land tenure, planning and management practices; resource inventories and production technology; crops and livesotck grown, cropping patterns and cultural practices; prices paid and received; and other data relevant to irrigated crop farming in the study area. These data were used to delineate size parameters and resource configurations of representative model farms.

The Programming Models and Assumptions

Linear programming models of representative farms were developed from detailed enterprise and resource budgets. A different model was used to describe each representative farming situation (or general case). Descriptive parameters of major importance include: farm size, enterprise alternatives, production levels, costs and returns, resource constraints, amoung others. Typical constraints faced by farmers, including limits on land, water, operating budgets, crop rotations, add realism to the "optimized" solutions and to the policy implications derived from them.

Farm size. The fact that size can have an important influence on operating efficiency and profit is well known. [Carter and Dean, 1961]. Whether or not Grand Valley farmers can harmlessly absorb the private costs of salinity abatements, costs which can be imposed on them directly or indirectly, depends in part upon their capacity to generate compensating revenues. Larger, more efficient farms are generally in a better position to meet additional obligations without materially affecting their operations or output. Smaller, less efficient farmers may not be so fortunate. The size distribution of farms, therefore, is an important consideration in modeling farmer response to various salinity control programs involving private costs.

On the basis of the sampled data, five model farm sizes were selected as representative of the size distribution of farms in the Grand Valley. These were farms of 40, 80, 130, 210, and 370 acres in size. A frequency distribution of sampled farms is reported in Figure 4. More than half of the farmers interviewed had operations of 120 cropped acres or less. Very few had farms of more than 300 acres. A high percentage of the smaller owner-operators work off the farm to support their families. These people

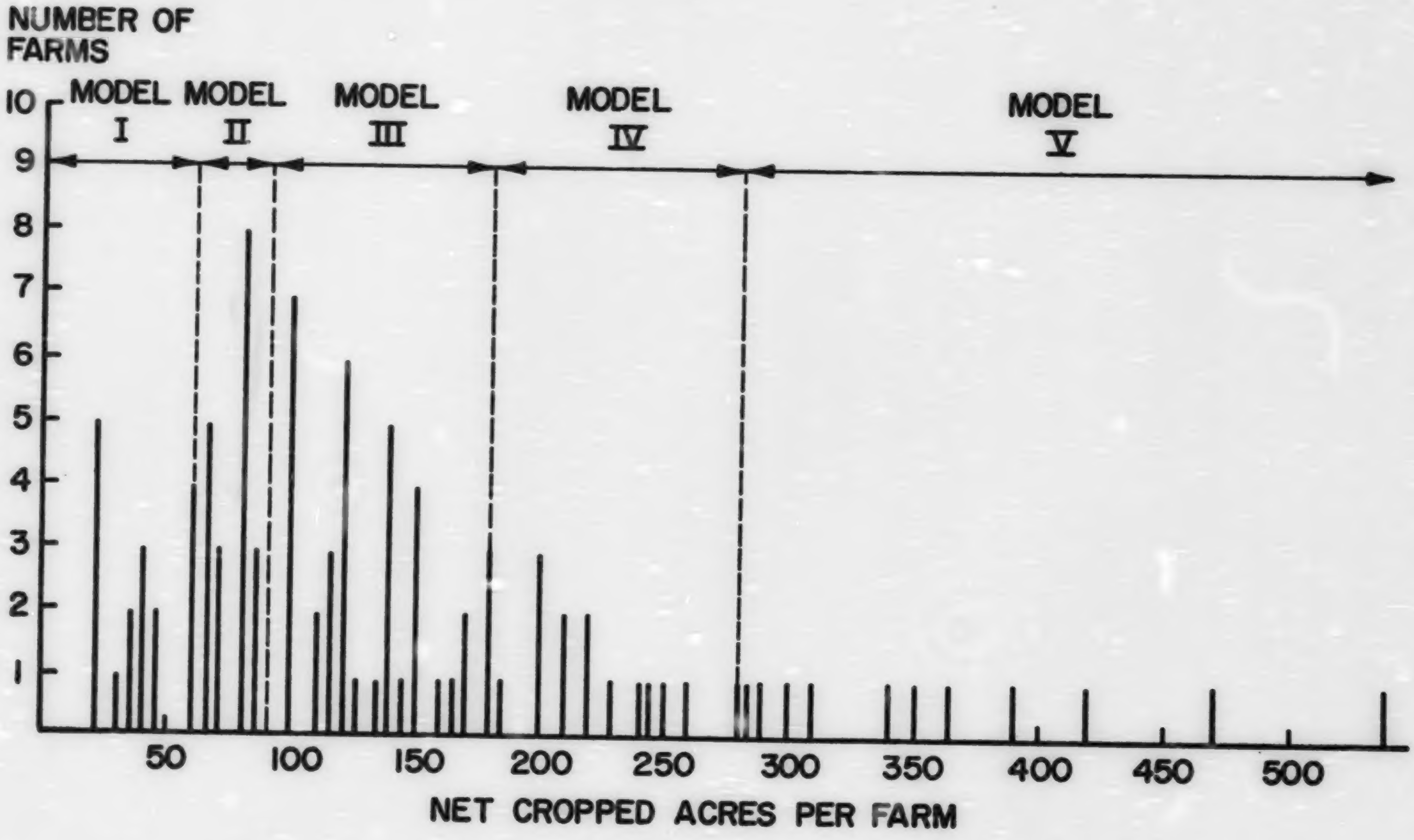


Figure 4: Frequency Distribution of Sample Farm Size and Model Acreage Parameters

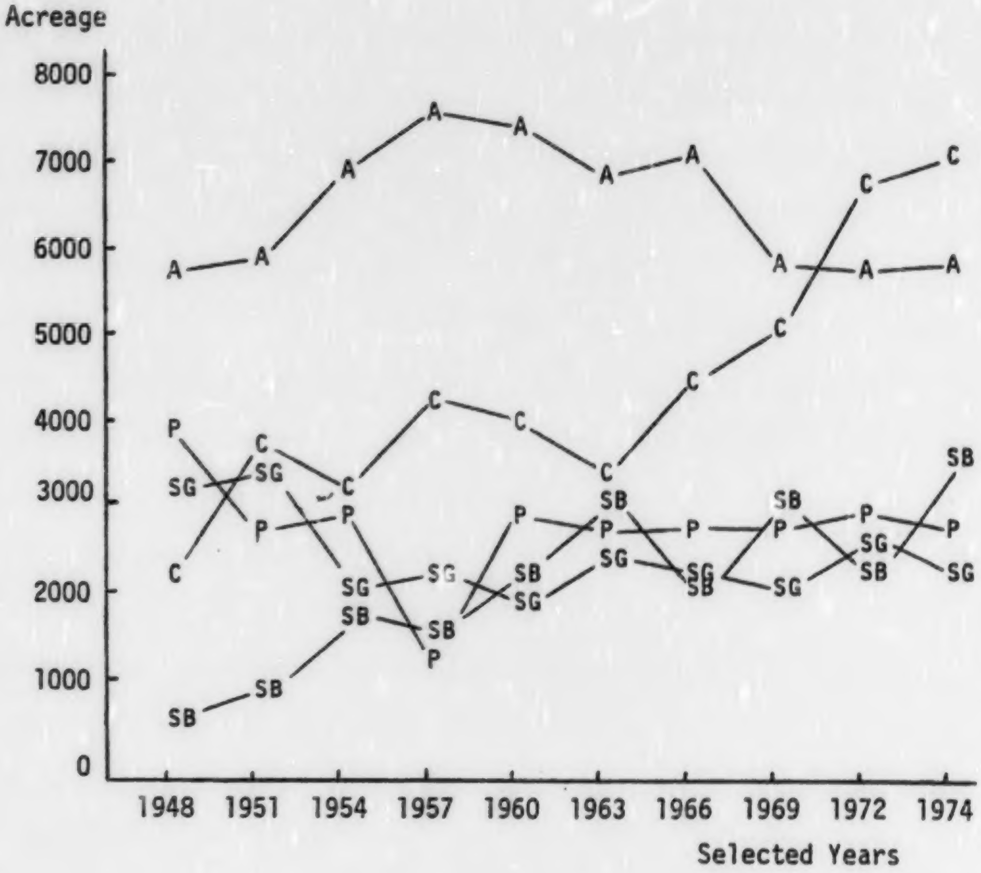
readily acknowledged that farming is not a primary source of family income. Rather, it is viewed as a "consumption" activity or ... "a nice environment for raising children". Judging from the number of individuals (with established water rights) excluded from the sample population because of the 40 acre cutoff, many families in the Grand Valley (perhaps 2,000 or more) are considered small-scale "farmers".

Production Possibilities. A moderately-long growing season (about 200 days) permits the production of a wide range of field, forage, vegetable and orchard crops in the Grand Valley. In terms of planted acreages, the most significant crops are corn, small grains (including wheat, feed and malting barley, and oats), sugar beets, permanent pasture and alfalfa hay. As indicated in Figure 5, planted acreages of these crops have remained fairly stable in recent years. Differences in crop mix with respect to farm size are described in Figure 6.

Orchard and other speciality crop enterprises, which account for about 15 percent of the total irrigated acreage, are quite diverse in ownership, production techniques, size of operation, and productivity. For this reason they are difficult to model with an acceptable degree of accuracy, and therefore were not included among the enterprise alternatives considered in the models. Further, no attempt was made to analyze in detail the many kinds of livestock enterprises found in the Valley. These are also very diverse in nature and would be difficult to model accurately.

Costs and Returns. Detailed enterprise cost and return budgets were developed to provide the necessary technical and revenue coefficients for the analyses. The unit budgets are model-specific, i.e. they are sensitive to farm size. Costs of production were calculated from 1975 input prices, and include all variable, fixed and overhead costs directly

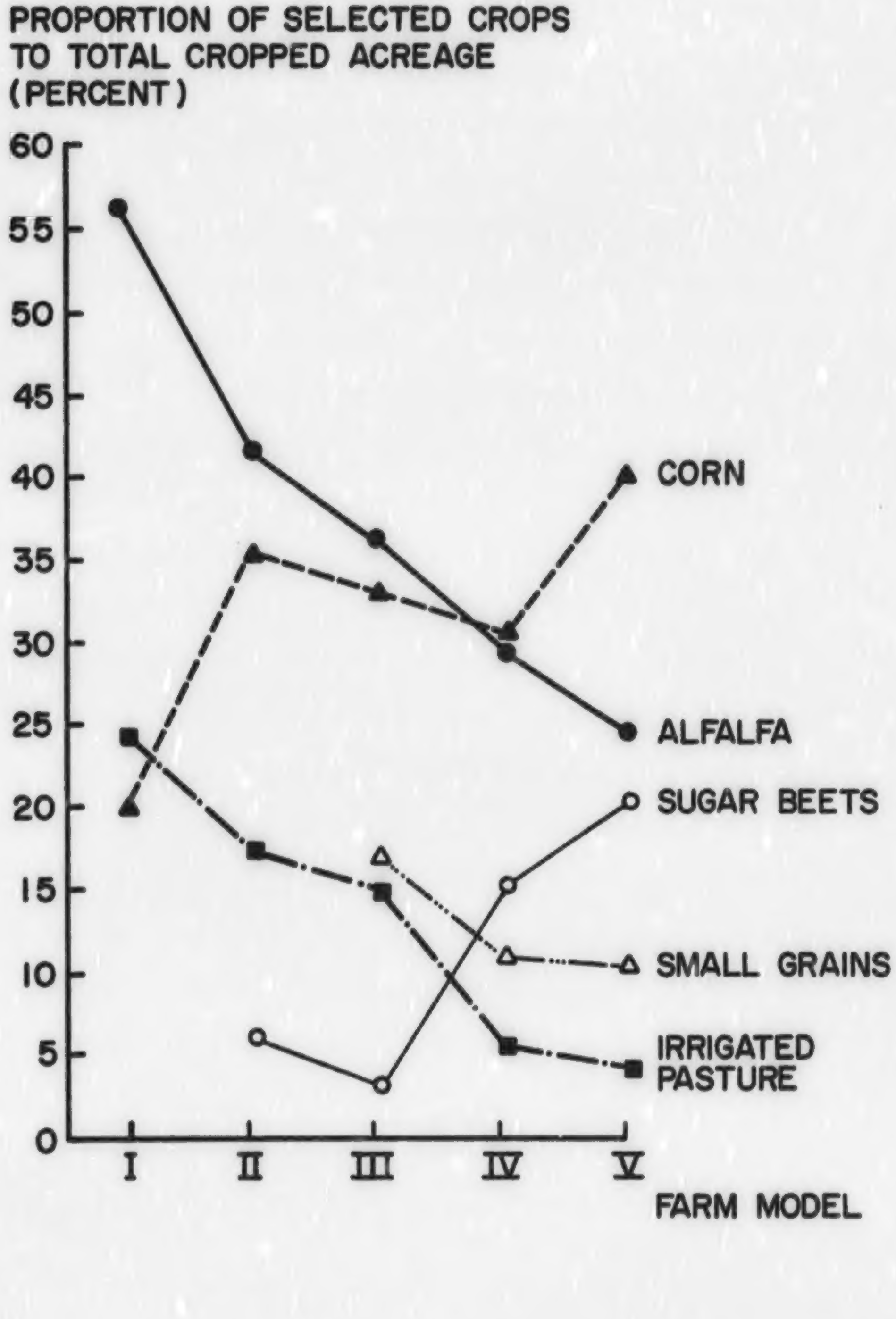
Figure 5. Harvested Acreages of Selected Crops Grown on Bureau of Reclamation Project Lands (Garfield Gravity Division) in the Grand Valley, 1948-1974



A = Alfalfa
P = Pasture
SG = Small grains
C = Corn
SB = Surgar beets

SOURCE: Grand Valley Water Users Association project records (selected annual production reports), Bureau of Reclamation project office, Grand Junction, Colorado.

Figure 6: Acreages of Selected Crops as a Percentage of Total Cropped Acres for Model Farms



chargeable to a particular crop enterprise. Fixed and unallocatable overhead costs were not included, hence net returns measure residual income above operating costs.

Gross sales were estimated using average yields for each farm size category and five year (1970-1974) average product prices. A price "weighing" procedure was thought to more accurately reflect long-run conditions for planning and evaluative purposes, since the price level for farm products has been abnormally high in recent years. Tables 1 through 5 in the Appendix section of the report summarize net crop returns and activity levels for each farm model. A detailed explanation of the budgeting procedure and summary of representative farms in the Grand Valley is reported elsewhere [Leathers, 1976b].

Resource and Other Constraints. Land available for irrigated crop production in the Valley has changed very little since the 1940's. Prior to that time significant acreages of land were abandoned. It has been estimated that as much as 20 percent of the once-irrigable land is idle due to high salinity and seepage problems resulting from poor drainage [Robinson, 1969]. Any future decline in the present irrigated area of approximately 56,000 acres would be primarily a consequence of suburban growth near Grand Junction and other smaller towns located within the Valley. Renovation of the drainage system (a proposed salinity control measure) could eventually increase the present acreage base by as much as 15 percent. This potential increase in the land resource was not considered in our analysis, nor was the possibility of developing new lands contiguous to present delivery systems. Following these assumptions the constraint on available crop land was set at approximately 47,500 acres, 85 percent of current irrigated land in the Valley.

As pointed out in Section II, water availability is not an important constraint on crop production. With the possible exception of peak consumptive use periods during July and August (when farmers in the Bureau of Reclamation project area may face limited water rationing) water supplies are well in excess of normal irrigation requirements. Since sufficient supplies are generally available during season (April to October), it was not necessary to distribute water supplies in a monthly or multiperiod format.

The base constraint used in the model is approximately 4.5 acre feet per acre on an annual basis. From this initial solution, water supplies are reduced in five percent increments of the original supply. This forces optimal responses to an increasingly severe constraint on alternative uses of water on the representative farms. Because of high groundwater salinity in the Valley, it is unlikely that pump water will be substituted for surface water as supplies are reduced. However, this possibility was not studied.

Acreage restrictions were placed on each crop in an attempt to maintain an aggregate (Valley-wide) cropping pattern reasonably close to the present crop mix. The cropping pattern in 1973 was used as the base year for setting the limits on allowable shifts in crop acreage. A minimum acreage base was established for feed grains and forages since these crops are low income earners in relation to others. Maximums and minimums were set for corn and sugar beets. The limits used (which are shown in Tables 1 through 5, Appendix) allow substantial shifting in crop mix to occur in response to limited water supplies. But a degree of realism is maintained by allowing acreage changes to go only so far, since "other" factors besides profit and efficiency criteria determine the Valley cropping pattern, but nonetheless cannot be included in models of decision behavior.

Modifications in Irrigation Practices

Irrigation is one of the most time-consuming tasks on Grand Valley crop farms. Many of the smaller farms, which account for a significant portion of total irrigated acreages, are managed by owner-operators who maintain part-time or full-time jobs off the farm. They accomplish farm work after normal working hours and on weekends. Accordingly, irrigation settings are usually changed at 24 or 48 hour intervals, i.e. once a day either before or after work. Because irrigations are worked around other farm tasks, larger farms typically follow the same practice. As noted earlier, low cost for incremental water deliveries (about $2.00 per acre foot) and non-enforcement of water rights provide a situation in which there is little incentive for using water efficiently.

The additional cost of reducing the length of an irrigation set (reducing the amount of water applied and the time of water intake) involves no real resource costs. The tasks involved in changing sets must be performed in any case. However, an "inconvenience cost" is incurred, since, for row crops, the operator would have to set up and monitor his water twice each day at twelve hour intervals rather than once per day as is typical at present. There is no particular empirical basis upon which to assign an accounting price to this apparent inconvenience. Our crude approximation consisted of using a charge for the relevant irrigations amounting to twice the normal irrigation wage to reflect an "overtime" labor requirements. This figure, twice the prevailing irrigation wage, is also close to the average off-farm wage in the area, and might be construed as an opportunity cost for those employed off the farm.

A number of assumptions regarding present irrigation labor requirements were made to obtain an estimate of the additional labor (or convenience) required to make the necessary modifications. These assumptions, in the form of labor input coefficients for a given irrigation set, under specified operations and conditions, are summarized in Table 1.

First, a reasonable labor input requirement for each irrigation situation was assumed (i.e., for a particular crop or row spacing siphon discharge rates per furrow, water supply at the farm headgate, and irrigation timing during the season.) The labor input was specified on the basis of two compenents: (1) setup time, which included moving canvases or portable dams, starting the siphon tubes, and adjusting siphon flow; and (2) monitor time, which includes clearing clogged furrows, managing field tailwater, and periodic checks of the field. A further refinement was made to allow for variations due to seasonal conditions. The first two irrigations in the spring typically require more attention (monitor time) than those that follow primarily because of differences in soil characteristics and cultural practices. The assumed labor coefficients reported in Part A are not experimental but are thought to be reasonable and valid for the purpose at hand.

Irrigation set times were reduced from 24 to 12 hours for corn, small grains, and sugar beets and from 48 to 24 hours for permanent pasture and alfalfa. The inconvenience cost was determined by multiplying the additional labor time by a charge twice the normal wage of $2.25 per hour. A similar (though weaker) argument is made for changing alfalfa and pasture irrigation from two to one day sets. The procedure allows for

TABLE 1. ESTIMATES OF ADDITIONAL LABOR (INCONVENIENCE) COST TO FARMERS FOR SHIFTING FROM PRESENT TO MORE EFFICIENT IRRIGATION PRACTICES

ITEM	DISCHARGE RATE PER FURROW[a/]	
	8 gpm	4gpm
A. LABOR REQUIRED PER SET:		
	--------- Hours ---------	
Set up time	1.5	2.0
Monitor time:		
First two irrigations (ea.)	3.0	4.0
Later irrigations (ea.)	1.5	2.0
Total labor time:		
First two irrigations (ea.)	4.5	6.0
Later irrigations (ea.)	3.0	4.0
B. ACRES IRRIGATED PER SET:[b/]		
	--------- Acres ---------	
Furrow spacing:		
24 inches	2.06	4.11
30 inches	2.57	5.12
C. HOURS OF LABOR PER ACRE:[c/]		
	------ Hours/Acre -------	
First two irrigations (ea.)		
24 inch spacing	2.18	1.46
30 inch spacing	1.75	1.17
Later irrigations (ea.)		
24 inch spacing	1.46	.97
30 inch spacing	1.17	.78

D. ANNUAL IRRIGATION LABOR COST:[d/]

Crop	Present Practices	Modified Practices	Additional Cost
	------------	$ per acre	-----------
Corn	18.44	22.38	3.94
Small grains	14.92	18.86	3.94
Sugar beets	22.14	27.05	4.91
Permanent pasture	16.68	20.62	3.94
Alfalfa	16.68	20.62	3.94

---

a/ Assumes water supplied at the farm headgate at a rate of 1 cfs per 40 acres net of on-farm conveyance losses.

b/ Number of acres capable of being irrigated with 1 cfs per 40 acres water supply.

c/ Labor requirements per set (part A) ÷ acres irrigated per set (part B).

d/ All cost estimates based on $2.25 per hour wage rate.

increasing irrigation labor costs to farmers as a result of adopting a more efficient irrigation practice, while the actual labor time on a per unit basis (the total irrigation labor input per acre per year) remains the same. Annual irrigation labor costs with and without this modification are compared in Part D. These costs of adopting the more efficient irrigation practice are, to emphasize, not real resource costs, and may be an over-estimate of the actual inconvenience to the farmer.

C. IRRIGATION-SALINITY RELATIONSHIPS

To identify the consequences of modifying irrigation practices on deep percolation (and subsequent salt pickup), a substantial amount of information about soil-water-crop relationships is required. Furthermore, this information, if used in an analytical model to deduce policy implications, must be both reliable and representative of actual conditions and practices.

A simplified soil-water-crop budget was developed to trace the effects of various salinity control programs on water utilization, plant growth and salinity in the Grand Valley [Leathers and Franklin, 1975]. The budgeting model focuses on deep percolation and seepage mechanisms and attempts to estimate empirically the rate of salt pickup in irrigation return flows. The results of this investigation and the policy implications are summarized here.

The Soil-Water-Crop Budget

The Grand Valley is characterized by considerable heterogeneity in soil conditions, topography, operating procedures of irrigation companies and districts, and farm production practices. Accordingly, the data summarized herein represents a careful selection of available information thought to be broadly representative of the Valley as a whole.

Typical irrigation practices followed by farmers and resulting implications for seasonal soil moisture depletion and crop evapotranspiration are described in Table 2. These observations do not differ markedly from similar data reported by others [Bureau of Reclamation, 1974]. In Table 3 the results of the budgeting model are summarized. The most critical budgeting assumption is the seasonal variation in water intake rates. Two seasonal conditions, early and mid-late season, are assumed to represent the change in water infiltration as the irrigation season progresses. A more precise approach would call for a specified rate for each sub-period (e.g., at each irrigation) since the actual change is more gradual [see Skogerboe, et al., 1973 and 1974; and Gilley, 1968]. Nonetheless, our results pose some interesting policy implications for control of on-farm salinity.

First, it is apparent that all crops do not contribute to deep percolation uniformly. Annual crops generate a deep percolation percentage (or leaching fraction) of 20 percent or more with small grains having the highest at 28 percent. Perennials contribute significantly less to deep percolation, since these crops have high evapotranspiration demands and are more likely to be stressed rather than overirrigated (see Table 2). But if stress should occur early in the growing period--enough to sufficiently reduce plant populations--the likelihood of greater deep percolation occurring later in the season (and in subsequent years) would be much higher.

Second, farm irrigation efficiency and deep percolation are not always closely related. That is, reduced deep percolation does not necessarily follow from improved irrigation efficiency. Because of the seasonal nature

Table 2. Traditional Irrigation Practices and Soil Moisture Relationships for Selected Crops in the Grand Valley[a]

ITEM	CROP Corn	Small Grains	Sugar Beets	Pasture	Alfalfa
Number of Irrigations	8	6	9	7	7
Number of Pre-irrigations	1	---	---	---	---
Cumulative ET (inches)	26.5	20.9	31.6	30.12	32.16
Mean ET per Irrigation[b]	3.35	3.45	3.48	4.30	4.59
Root Zone Storage (inches)	9.2	9.2	9.2	9.2	14.0
Soil Moisture Depletion at Each Irrigation[c]	38%	38%	38%	47%	33%
Irrigation Interval (days)[d]					
Longest	42	27	34	31	25
Shortest	9	9	12	19	18
Length of Irrigation Set (Hours)					
First two irrigations	24	24	24	48	48
All others	24	24	24	24	24

a/ Assumes a normal growing season.

b/ Cumulative ET ÷ number of irrigations per season.

c/ Mean ET per irrigation ÷ root zone storage capacity.

d/ Number of days between irrigations where cumulative ET reduces the percent available soil moisture to the indicated levels.

Table 3. Water Budget Summary for Traditional Irrigation Practices in the Grand Valley: Annual Water Use and Losses for Selected Crops

ITEM	CROP				
	Corn	Small Grains	Sugar Beets	Pasture	Alfalfa
	Annual AF/A				
Water Applied[a/]	3.74	2.98	5.28	4.80	4.80
Root Zone Additions	2.94	2.40	3.27	3.06	3.06
Crop Consumptive Use	2.21	1.74	2.63	2.51	2.68
Deep Percolation	.73	.66	.64	.55	.38
Field Tail Water	.80	.58	2.10	1.74	1.74
Farm Irrigation Efficiency[b/]	59%	58%	50%	52%	56%
Leaching Fraction[c/]	25%	28%	20%	18%	12%

[a/] "Net" of on-farm delivery losses.

[b/] Defined as crop consumptive use ÷ water applied.

[c/] Defined as deep percolation ÷ root zone additions.

or infiltration rates for Grand Valley soils, in all but about the first two irrigations water applied in excess of the amounts indicated for a 24 hour set would lower irrigation efficiency (by increasing tailwater loss) but not measurably alter deep percolation. Therefore, salinity controls which involve improving irrigation efficiency need only concentrate on the first part of the irrigation season and should be crop-specific.

Farm irrigation efficiency studies conducted in the Valley during the 1950's by the Bureau [1957] and more recently by Skogerboe and Walker [1973], estimated overall efficiency at 40 percent. This does not agree with the results of our aggregated water budget, which is compared with Skogerboes' in Table 4. Although some cropped acreage is omitted in the computations (approximately 8,500 acres of orchards and speciality crops), our findings differ most significantly on the estimate of deep percolation. Our own estimate of water use and deep percolation are used for analysis purposes, since these are believed to be a middle ground for available estimates of these parameters.

Rate of Salt Pickup in Return Flows

In the Grand Valley seepage and deep percolation waters do not return to the river as direct, separable flows but mix with saline waters contained in gravel-cobble acquifers. This mixing of return flows with acquifer water is supported by the observation that surface return flow in open drains (typically very low rates of flow) couldn't by itself account for the total salt pickup [Kruse, 1975]. Both seepage from canals and deep percolation water create a hydrostatic pressure gradient, forcing some saline water out of the gravel-cobble acquifer into the river. For

Table 4. Comparison of Total Water Budgets for Irrigation in the Grand Valley: Aggregate Use and Losses

ITEM	TOTAL VALLEY BUDGET[a]			CROPS-ONLY BUDGET		
	AF	AF/A	Percent	AF	AF/A	Percent
	- - - - - - - - - - - - -	annual	summary - - -	- - - - - - -	- - - - - -	- - - - -
Water Applied	373,000	6.2	100	214,380	4.4	100
Root Zone Additions	211,000	3.5	57	147,146	3.0	69
Crop Consumptive Use	150,000	2.5	40	126,310	2.5	59
Deep Percolation	61,000	1.0	16	20,836	.42	9
Field Tail Water	162,000	2.7	43	67,234	1.4	31
Total Acreage		60,800			47,480[b]	

[a] Adapted from Skogerboe, et al., [1974].

[b] Excludes orchard, truck, and other speciality crops.

this reason it is difficult to assess the relative importance of canal and lateral seepage and deep percolation because there is no easy way to measure and differentiate the return flows as two different mechanisms. A further complication stems from the practice of farmers to run "tail" water into the open drains and natural washes during the irrigation season thus diluting the concentration of drainage water.

The ionic constituents and ion ratios of drainage, acquifer, ground, and river water entering and leaving the Grand Valley area were compared in an attempt to derive empirical estimates of salt pickup. The ion contents were used to calculate an average salt pickup rate per acre-foot of deep percolation water. To obtain an estimate of the average ionic composition of diverted river water, various data from the U.S.G.S. sampling station located at Cameo were used [U. S. Geological Survey, 1966-1970]. The period of analysis was April through September, 1966-1970.

Based on these inflow data, theoretical equilibrium compositions of soil water were calculated to compare results for different assumed leaching fractions. The predicted equilibrium values, reported in Table 5, were obtained from a computer program developed by Rai and Franklin [1973]. The model compares results with a nongypsiferous, calcareous soil type, and calculates the drainage water composition if no 'fossil" or soild phase salts are dissolved from the subsoil. According to salt balance theory, different fractions of irrigation water (leaching or deep percolating water) applied to growing crops result in different ion concentrations in soil water at the bottom of the root zone. Assuming that the soils contained lime ($CaCo_3$) but not gypsum or other soluble salts associated with the shale substrata, the drainage waters should be comparable to those shown.

Table 5. Average Composition of Colorado River Water Diverted for Irrigation and Predicted Ionic Equilibrium Compositions for Various Leaching Fractions

Constituent	Diverted River Water[a/] (average)	Percent Leaching Fraction 30	25	20	10	5
	me/l	- - - -	equilibrium values in me/l[b/]			- - - -
Ca	2.71	3.96	4.10	4.47	6.18	9.43
Mg	1.27	4.23	5.08	6.35	12.70	25.40
Na	3.10	10.33	12.40	15.50	31.00	62.00
K	.07	.23	.28	.35	.70	1.40
HCO_3	2.39	2.74	2.84	2.89	2.90	3.03
SO_4	2.00	6.67	8.00	10.00	20.00	40.00
$CL+NO_3$	2.76	9.20	11.04	13.80	27.60	55.20
$CaCO_3$	.02	5.42	6.74	9.09	20.92	24.77

Average TDS/AF = .7 tons

[a/] Quality of water at Cameo, Colorado, or approximate point of diversion for irrigation.

[b/] Obtained from a computer program developed by Rai and Franklin [1973]. me/l = milliequivalents per liter.

The data illustrate that only $CaCo_3$ would be expected to precipitate. As irrigation becomes more efficient, (i.e., the leaching fraction is reduced) Mg, Na, SO_4, and Cl would increase to relatively high value.

Estimates of the quality of drainage water was facilitated with the use of water samples taken from natural drains in early 1975 (January and February). Detailed analyses of the samples were conducted by Agricultural Research Service personnel [Kruse, et al., 1975]. Average ion concentrations for the Little Salt, Big Salt, Adobe, Persigo, and Hunter drain outlets are summarized in Table 6. The ionic composition is reasonably consistent among the different drains, although average TDS varies between 3.1 and 4.6 tons per acre foot (T/AF). Using a value of 0.7 T/AF to approximate the TDS of diverted irrigation water, the average net salt pickup for all the drains amounts to about 3.2 T/AF. This value might be representative of salt pickup in deep percolation and seepage waters, not associated with the gravel acquifer, but which are intercepted by the drainage system. Also, since TDS concentrations of drainage waters are highest in the winter months, the estimate of 3.2 T/AF is probably a maximum value.

A similar procedure was used to estimate ground water salinity. Ground water analyses of 11 wells located in an area east of Grand Junction to Bethel Corner, of four wells near Fruita (all in the gravel acquifer), and of 25 wells located north of the acquifer are summarized in Table 7. The approximate location of these sampling sites is shown in Figure 3, section II.

The acquifer waters near Fruita apparently contain about one-half the TDS of those to the east of Grand Junction. This illustrates the uncertainty in estimating an average rate of salt pickup in that salt

Table 6. Ionic Analyses of Drainage Waters for Selected Drain Outlets in the Grand Valley: Averaged Concentrations, January and February, 1975

Wash or Drain	EC x 10^3 mmhos/cm	Ionic Constituent in me/l								TDS in Tons/AF
		Ca	Mg	Na	K	HCO_3	SO_4	CL	NO_3	
Little Salt	3.71	16.5	12.8	20.4	.2	7.2	40.6	6.5	1.0	4.4
Big Salt	3.07	15.9	12.8	12.0	.3	7.1	29.7	4.1	0.5	3.1
Adobe	3.90	17.7	16.7	20.4	.3	7.3	40.9	6.6	1.0	4.6
Persigo	3.12	234.2	8.0	11.1	.2	4.4	37.2	3.6	0.3	3.2
Hunter	3.67	19.8	18.1	14.6	.4	6.5	41.9	5.6	0.7	4.4
Average	3.49	18.8	13.9	15.7	.3	6.5	38.1	5.3	0.7	3.9

Table 7. Ionic Analyses of Ground Waters at Two Locations in the Gravel-Cobble Acquifer and at One Location North of the Acquifer: Averaged Concentrations

Location	EC x 10^3 mmhos/cm	Ionic Constituent in me/l								TDS in Tons/AF
		Ca	Mg	Na	K	HCO_3	SO_4	CL	NO_3	
Acquifer Waters:										
Grand Junction Area (11 wells)	6.03	23.3	39.4	32.7	.4	8.5	74.6	11.0	1.2	8.5
Fruita Area (4 wells)	3.88	18.0	13.5	24.5	.4	4.6	50.6	7.0	.3	4.6
Average	4.96	20.6	26.4	28.6	.4	6.6	62.6	9.0	.8	6.6
Waters North of the Acquifer:										
(25 wells)	4.92	18.1	19.1	51.9	.4	7.9	68.0	9.6	1.9	5.9
Overall Average	4.94	19.4	22.8	40.2	.4	7.2	65.3	9.3	1.3	6.2

concentrations within and outside of the gravel acquifer are noticeably different. However, when the acquifer concentrations are averaged together the resulting concentration is close to that of the ground water. Total dissolved solids for averaged acquifer waters is 6.6 T/AF compared to the average ground water concentration of 5.9 T/AF.

To obtain a salt pickup rate which is representative of "mixed" return flows (i.e., some combination of surface drainage and acquifer waters) it is necessary to weight the relative concentrations by the appropriate magnitudes of flow. Subsurface return flows (deep percolation and seepage water) were assumed to comprise about 80 percent of the total return flow from irrigation, and water intercepted by surface drains about 20 percent. This proportion reflects a concensus among researchers based on limited measurements [Olsen, 1975]. Three estimates of the average (Valley-wide) salt pickup rate, based on this 80:20 weighting scheme, are reported in Table 8.

A pickup rate of 5.36 T/AF reflects a combination of acquifer and surface drainage waters. This rate might be representative of the irrigated acreage situated over the acquifer. Ground and surface waters together yield a pickup rate of 4.89 T/AF, possibly representative of irrigated acreage located north of the acquifer. Our choice of an average salt pickup rate was the third option, 5.04 T/AF, a combination of all return flow sources. This rate represents an average for the Grand Valley and reflects a compromise among different rates of salt pickup associated with the various pickup mechanisms. A more detailed description of the data and procedures used is also contained in the Leathers-Franklin manuscript [1975].

Table 8. Average Salt Concentrations for Sources of Surface and Subsurface Irrigation Return Flows and Weighted Estimates of Average Rates of Pickup

Item	Surface Drains	Acquifer	Ground Water	Combined Subsurface[a/]		Average Pickup Rate(T/AF)
	RETURN FLOW SOURCE AND QUALITY					
	- - - - - - - TDS in Tons/AF - - - - - - -					
Mean Values	3.9	6.6	5.9	6.2		
Less: TDS Inflow	.7	.7	.7	.7		
Net TDS Outlfow	3.2	5.9	5.2	5.5		
Weighting Scheme:	Percent of Total Return Flows					
	20	80			=	5.36
	20		80		=	4.80
	20			80	=	5.04

---

a/ Simple average of acquifer and ground water concentrations.

A note of caution in using this figure should be mentioned. This estimate of 5 T/AF is based on calculations which assume that the total annual salt pickup is attributable only to irrigated agriculture. Significant contributions of salt from natural runoff (if they prove important) will cause the control effectiveness of on-farm measures to be overestimated.

D. RESULTS AND SUMMARY

It was hypothesized that improved efficiency in on-farm water use, stimulated by constraining water deliveries to farms, would reduce salinity in irrigation return flows. The direct costs of these farmers response strategies, namely, improved irrigation techniques, crop substitutions, and use of aluminum pipe, were derived with linear programming models of representative farms. A soil-water-crop budget was used to measure the appropriate water use and salinity coefficients with which to evaluate cost effectiveness. In this section, the results of our analyses and policy implications are summarized.

Estimated Costs for Control of Deep Percolation

Aggregated results of our analysis dealing with control of deep percolation are summarized in Table 9. Row [1] portrays our estimates of existing conditions, while row [2] is the initial or benchmark solution of the five programming models in which irrigation water is nonlimiting. Subsequent rows represent the predicted effects of successive 5 percent reductions in available water supply on salt discharge, net crop income and crop acreage. The estimate of salt discharge is based on the rate of 5 tons per acre foot of deep percolation water.

Table 9. Estimated Annual Direct Income, Crop Substitution and Salinity Effects of Limiting Irrigation Water Delivered to Farms

	Irrigation Water Deliveries a/	Salt Discharge in Irrigation Return Flows b/	Total Net Crop Income	Incremental Income Loss of Salt Removal c/	Cropping Pattern of Model Farms					
					Corn	Small Grains	Sugar Beets	Pasture	Alfalfa	Total Acreage
	A. INITIAL CONDITIONS d/									
[1]	214,745	146,540	5,962,301		13,893	6,460	3,582	13,328	13,895	51,158
[2]	201,234	147,813	7,915,230		23,897	2,730	7,635	2,896	10,315	47,473
	B. INCREMENTAL REDUCTION IN IRRIGATION WATER SUPPLY e/									
				2.04						
	191,173	131,594	7,882.176		23,897	2,730	7,635	2,896	10,315	47,473
				1.88						
	181,111	112,125	7,845,633		23,897	2,730	7,635	2,896	10,315	47,473
				1.65						
	171,049	86,601	7,803,431		23,897	2,730	7,635	2,896	10,315	47,473
				1.69						
	160,987	51,635	7,744,495		23,864	3,038	7,635	2,896	10,040	47,473
				18.88						
	150,926	30,370	4,343,006		19,413	10,245	7,635	2,896	7,284	47,473
				85.31						
	140,864	18,205	6,305,168		13,677	19,858	7,617	2,896	3,425	47,473
				406.26						
	130,802	15,525	5,216,403		7,370	28,350	4,944	2,896	2,913	47,473
				293.36						
	120,740	7,211	2,777,371		7,370	31,092	3,202	---	2,913	44,577

a/ Water is measured as deliveries to farm headgates.

b/ Based on an assumed pickup rate of 5 tons of salts per acre foot of deep percolation water.

c/ Defined as the change in income per unit change in salts removed.

d/ Row [1] represents the assumed present conditions. The estimates apply only to irrigated crops, since specialty and orchard enterprises are not included in the farm models. Row [2] is the base solution of the L.P. model with no constraints on water supply.

e/ Successive increments are withheld at five percent of the initial supply (part A, [2].)

In general, our results indicate that substantial reductions in this particular portion of salt discharge are possible at relatively low cost. The first twenty percent reduction of water supplies is absorbed inexpensively by more efficient irrigation techniques, yet estimated salt discharge is reduced by 96 thousand tons over this range. About 62 percent of the estimated on-farm initial salt discharge appear to be avoidable at costs to farmers of less than $2.00 per ton. These results are consistent with similar studies reported by Anderson, et al., [1974]. However, once water use is reduced to minimum evaporative and leaching requirements, savings take place only by crop substitution and actual cessation of crop production, at much greater cost.

The optimal (least cost) reponse of farmers to limits imposed on delivered water would be first to adopt the more efficient irrigation practice, namely to experience the inconvenience of having to irrigate twice in 24 hours rather than once for the first two irrigations of each crop. The alternative strategy of substituting crops, i.e., crops which contribute less to deep percolation for those which are more of a problem, becomes an efficient solution only following the complete adoption of the more efficient irrigation process for all of the crop activities. It was noted in Table 3 that corn contributes more to deep percolation than alfalfa: .16 acre feet and .02 acre feet, respectively. Using model III as an example (Table 3, Appendix), if substitution takes place (alfalfa for corn), the net change in income per acre, $89 minus $134 or -$45, divided by the net exchange of salt pickup (.16 minus .02 acre feet of deep percolation times five tons per acre foot), or .7 tons, gives a cost of $64.29 per ton. Although this is comparatively high, substituting lower value crops for corn would generate even higher costs.

Conversely, substituting sugar beets for corn would yield negative direct costs of removing some salts. Institutional and market constraints on the expansion of crop production (especially sugar beets), however, limits this type of crop tradeoff to a minimum in this analysis.

Reduction of salt loading attributed to crop substitution begins at the level of about 165,000 acre feet of water supply and ends at about 130,000 acre feet, or 3.3 and 2.7 acre feet per acre, respectively. Beyond a 2.7 acre feet per acre water supply, salts can be removed only by retiring some of the irrigated acreage base.

A sensitivity analysis of these costs with respect to assumed salt pickup rates and amounts of deep percolation suggest that the above estimates should be regarded with extreme caution. For example, if the amount of deep percolation per average acre in the Valley is reduced by half (from 5 to 2.5 inches) and the rate of salt pickup is reduced by half (from 5 to 2.5 tons per acre foot), the costs of improved irrigation practices will increase 4-fold, from $2.00 to about $8.00 per ton removed. Therefore, until the physical relationships are well established, the above conclusions should be regarded as preliminary estimates.

Estimated Costs of On-Farm Seepage Control

A second category of salt pickup associated with on-farm irrigation water management practices stems from seepage in the farm water conveyance system. On-farm conveyance losses are estimated to account for about the same amount of salt as the field losses just discussed, 150,000 tons per year. Aluminum pipe to replace laterals and gated aluminum pipe for head ditches represent a means by which ninety percent of present on-farm delivery seepage can be avoided.

Losses from the farm conveyance system (farm laterals and head ditches) could be influenced by constraining water deliveries, or encouraged by a subsidy program. If faced with a limited water supply it is quite likely that farmers would adopt such a strategy before they would engage in crop substitution. We estimate the cost of a 90 percent reduction in this portion of salt pickup can be achieved at an average cost of less than $8 per ton. The procedure and results supporting this conclusion are described in Table 10. Possible additional benefits which may accrue to farmers as a result of adopting gated pipe, e.g., increased yields through better control of irrigation water, and/or irrigation labor savings have not been included here since experience with this system in the Grand Valley is rather limited.

However, these estimates should also be regarded as provisional for the same reasons cited above. The cost effectiveness of on-farm control measures (or for that matter, any control) is more sensitive to the physical assumptions about salt removal than to assumptions of economics.

Summary and Implications

We have reported in this section the economic impacts of several alternative methods for reducing saline return flows from irrigated lands in the Grand Valley. Our analysis suggest that adjustments in on-farm water management practices are a relatively inexpensive methods of dealing with the problem. Other proposed structural measures appear to be considerably more expensive. However, several specific limitations should be recognized in interpreting the results of this analysis.

TABLE 10. ESTIMATED ANNUAL COSTS FOR REDUCING ON-FARM CONVEYANCE SYSTEM SEEPAGE WITH ALUMINUM PIPE IN THE GRAND VALLEY

ITEM	PER CROPPED ACRE	FOR 56,000 ACRES
A. MATERIALS REQUIREMENTS		
Unlined laterals and ditches replaced[a]	51.2 feet	543 miles
aluminum pipe and structures:		
8" pipe (laterals)	17.05 feet	180.8 miles
6" gated pipe (head ditches)	34.15 feet	362 miles
Concrete turnouts (one per 12 acres)		4,667
B. OWNERSHIP AND OPERATING COSTS		
New cost:[b]		
8" solid pipe ($2.18/ft.)	$37.14	
6" gated pipe ($1.78/ft.)	58.65	
Turnouts ($114.96 installed)	9.58	
Initial investment	$ 105.37	$5,900,664
Annualized costs:[c]		
Depreciation	$ 9.48	
Interest, insurance, and taxes	5.26	
Repairs and maintenance	4.21	
Total	$ 18.95	$1,061,368
C. CONTROL EFFECTIVENESS		
Salt pickup avoided with 90% efficiency	2.41 tons	135,000 tons
Average annual cost per ton	$ 7.86	

a/ These estimates are "net" of approximately 33 feet of unlined laterals per cropped acre (350 miles). Although situated within the confines of farms, these laterals are owned and maintained by the various irrigation districts.

b/ Pipe cost estimates (in 1975 prices) were obtained from local dealers. 100% replacement of all unlined laterals, and 50% replacement of all irrigation head ditches owned by farmers is assumed (see footnote a/. The number of concrete turnouts (from laterals to farm head ditches) reflects an average field size of 12 acres in the Valley.

c/ Calculated using conventional farm budgeting techniques assuming a useful life of 10 years and an interest rate of 6 percent.

First, neither the amount of drainage water associated with specified irrigation practices nor the rate of salt pickup per unit of drainage water are well established. In fact, considerable disagreement is found on these points among hydrology and soils specialists. A better understanding of the relative salt contribution of field percolation losses versus seepage from conveyance systems is also necessary before any definitive assessment of nonstructural controls can be achieved. Similarly, the relative contribution of the various crops needs to be established more precisely before the crop substitution alternative is rejected.

Second, it may not be possible to increase irrigation efficiency to the degree assumed without some sacrifice in crop yield. A small decrement in yield can have a significant impact on net returns to farmers. Similarly, unstable farm prices could make reliable estimation of program costs and benefits still more uncertain.

Third, for purposes of this analysis, we have assumed that farmers could in some way be costlessly persuaded to adopt more efficient irrigation practices. To assure uniform adoption of such practices would no doubt require a considerable regulatory and monitoring effort, which would be both expensive and unpleasant for all concerned. We have not dealt with the regulatory and social costs of imposing water quality standards (or constraints on water supplies) in this sort of situation where the effluent of individual irrigators is not identifiable. Present water distribution policies in the area and Colorado water law do not provide any incentive for reducing return flows, and relatively drastic penalties might be required to accomplish this. We have analyzed the technical and economic feasibility of the approach, but the political-administrative procedures for implementation remain to be specified and evaluated. The structural measures may be expensive, but they would be relatively straightforward to implement.

We also wish to comment on the incidence (that is, which groups bear the costs and benefits) of water-use efficiency measures to reduce salinity. The type of water use controls we have hypothesized have their impacts directly on the water-user's pocketbook. This is in direct contrast to the structural measures (canal lining, desalination, etc.) which are slated to be financed from federal appropriations. Our calculations indicate that up to about one-half of the estimated Grand Valley salt discharge could be avoided by more efficient water use on the farms themselves. However, the reduced income necessary to accomplish this would total over $1 million annually. Although this amount would not destroy the agricultural economy of the Valley, it represents a significant part of the return to the land and managerial resources. It seems, therefore, appropriate to give careful consideration to some arrangement for cost sharing.

Finally, we have not considered the questions involving use of water resources that might be released from agriculture as a result of implementing such programs. If alternative beneficial uses exist for "new" supplies (which incidently, could include bringing new lands under irrigation in the Grand Valley [Bureau of Reclamation, 1957]), salinity control costs may be partially mitigated by new developments or expansion of the present economy.

SECTION V

THE ECONOMICS OF LAND RETIREMENT AS A MEANS OF CONTROLLING SALINE IRRIGATION RETURN FLOWS

A. INTRODUCTION

Much of the research effort by physical and social scientists concerned with controlling rising levels of salinity in the Colorado River Basin has focused on structural technologies. These means typically require extensive technical and material input often leading to substantial public and private investments. This chapter reports an evaluation of land retirement as a salinity abatement option for implementation in the Grand Valley. Land retirement is one nonstructural control option that deserves careful empirical study since acreage reduction is the only technically feasible method which can achieve the zero discharge objective proposed in the 1972 federal water quality legislation (Public Law 92-500).

To determine whether land retirement can be feasible on economic efficiency grounds, two sources of information are required: (1) the direct and indirect costs of removing land from irrigation, and (2) the benefits or incremental reduction in damages that would occur as a consequence. Direct costs should accurately reflect the incomes foregone from farming of the retired irrigated lands. Included in the indirect costs should be the net effects of costs and benefits issuing from resource reallocation, social transition, impacts on environmental amenities, and other consequences in the affected region. Program benefits may also involve direct and indirect effects: direct benefits represent the increment of technological externality removed or penalty cost avoided, and indirect benefits (or costs) are impacts which "stem from" the direct effects. Land retirement is said to be economically feasible only if long run net benefits can be demonstrated, i.e., if incremental benefits exceed incremental costs over the life of the program.

An interindustry (input-output) model serves as the underlying structure for this analysis. The input-output model is an analytical accounting technique commonly used in the evaluation of "total" economic impacts of exogenous (or outside-induced) change in an economy. Because of the interdependence among industries in a well developed economy (which may include small or large regions), secondary (or indirect) impacts are often thought to be just as important as the primary (or direct) impacts of an induced change. For this reason the basic approach adopted in this study is indirect impact analysis.

This section is organized into four subsections. In Part B our approach to the problem and the basic assumptions which underlie our analyses are discussed in some detail. A discussion of results is presented in Part C. These results pertain to both local effects in the Grand Valley area and to the impact on the State's economy. The last part, Subsection D, is devoted to an overview of the chapter with emphasis placed on the limitations of the study and some implications for more definitive research on the topic.

B. APPROACH AND ASSUMPTIONS

Land retirement mechanisms might include one or more of a number of options, and can be either voluntary or involuntary depending on the level of public acceptance and participation in the program. The objective is to discontinue irrigation on selected acreage, thus eliminating all future salt loading from these sources. Specific program options evaluated here involve a permanent withdrawal of water supplies.

Compulsory vs. Noncompulsory Programs

Withholding irrigation water from previously cultivated acreage in the Grand Valley might be accomplished on a voluntary basis by State purchase of existing water rights from willing sellers [Trelease, 1960]. Because of the Grand Valley's arid climate, this would mean that farmland is taken out of production altogether, eventually returning to desert. State purchase of privately-held water rights from legal condemnation proceedings would constitute a compulsory mechanism [Gross, 1965]. Both would, in effect, amount to land purchase since desert-grazing land is of nominal value by comparison.

If a voluntary land retirement program is to be viable, this implies that some farmers in the Valley would be willing to sell their farms (or a portion of their acreage) at a price that exceeds the present value of their long-run, capitalized earnings. In the case of "marginal" farms, this would mean that some individuals would be willing to trade the present value of farming (in the long run) as a "consumption activity" for an alternative activity made available by the purchase offer. Under an involuntary program, it would probably be necessary that the offer price exceed the present market value of representative irrigated acreage. The program would have an added flexibility if willing sellers under a voluntary retirement scheme could select the marginal acreages on their farms (perhaps difficult areas to irrigate where water losses are high and productivity low) for purchase by the State -- analogous to the soil bank program [Public Law 89-321]. Under such an option the costs of the program might be reduced appreciably.

Partial vs. Complete Retirement

Two different program options are examined. The first option (which we label Option I) represents a partial retirement scheme. Specific areas of irrigated land which are markedly less productive (since they tend to have high salt content and/or serious natural drainage problems that hinder plant growth) are selected for retirement. Chief among the soil groups that fit this description are those silty clays and clay loams derived residually from Mancos Shale [Knobel, 1955]. Although these soils typically exhibit poor yields as compared with the remainder of the area, conventional irrigation practices are normally followed resulting in deep percolation and seepage losses equivalent to the area averages. Approximately 8,600 acres in the Grand Valley (as well as 10,200 acres in the neighboring Uncompaghre Valley) fall into this category. Together they represent 15 percent of the area's irrigated lands and 8 percent of the areas' crop output. Since these areas of relatively unproductive soils are not contiguous in large blocks, retirement of such lands would control deep percolation from fields and seepage from farm laterals and head ditches, but would not account for seepage losses in the main distribution system.

A different strategy (Option II) considers the effect of retiring an entire irrigation district. All canals and laterals controlled as an integrated unit and the acreage (both poor and productive) they service would be withdrawn from production. With this option, land retirement implies the inclusion of canal and lateral seepage losses which would be excluded under the first option. Accordingly, we compute the costs of retirement on the basis of two assumed rates of annual salt reduction per acre: 5.4 tons under Option I, and 8.2 tons under Option II. A sensitivity of program costs to these estimates is also reported. The Government Highline Canal, a Bureau of Reclamation project operated by the Grand Valley Water Users Association and which serves approximately 20,500 acres of irrigated crops, was chosen to illustrate the impacts of Option II. It is assumed that this district is representative of the Valley as a whole in terms of both productivity and salt pickup, so that results could be generalized to a full retirement program.

Valuation of Land and Water Resources

The selection of a method for valuing irrigated lands to be retired is dependent upon ownership and use. Capitalizing future earnings of a marginal farm, situated in an area where the fair market value of comparable land is well in excess of the capitalized value, is certainly not a workable approach under a voluntary program. Income capitalization is a relatively precise method for valuing a productive resource, but its applications are limited in some circumstances. As a general rule market forces have a more direct influence on property values.

Speculative market values reflect alternative uses as well as present use, and, accordingly, market values tend to run higher than capitalized values for the same resource. But in cases where land has only one use (its present use), capitalized and fair market values converge. This phenomonen is usually observed in traditional agricultural areas such as the midwest, and is likely true in the Grand Valley. Larger, more efficient farms typically establish land prices through marginal additions to land holdings thereby setting a general price level which prevails for other farmers in the immediate area [Tweeten, 1971]. For this reason the income approach was used in this analysis to approximate the market value for land and water resources.

Income losses from a land retirement scheme can be measured by the foregone net income from land and immobile improvements (mainly the irrigation distribution systems). The estimated income residual allocated to these resources will vary with farm size and soil productivity, among other factors. Our procedure for determining the residual return to land and immobile improvements is based on traditional crop share rents in the study area. The landowner typically receives one-third of the gross crop sales, but is responsible for a similar proportion of fertilizer expenses as well as for all real estate taxes and water charges. Gross sales on the low productivity lands (Option I) were estimated at $177 per acre (1975 price levels), while the estimated average of all lands was $349 per acre [Leathers, 1976b]. Computing the landowner's share (one-third) and deducting fertilizer, tax and water charges yield annual net returns foregone of $39 for Option I lands and $90 for Option II. Capitalized at 6 percent over an infinite time horizon these rates of return translate to present values of $650 and $1,500 per acre respectively. The current asking price of productive irrigated land in the Grand Valley ranges upward from $1,500 per acre [Mesa County Assessor's Office, 1976].

The market value for less productive acreage is not known. At these prices, the costs of retiring cropland per ton of salts avoided, in annual terms, would be $7.22 under Option I ($39 ÷ 5.4 tons per acre) and $10.98 under Option II ($90 ÷ 8.2 tons per acre).

Analysis of Direct and Indirect Impacts

We estimate the direct and indirect impacts of the two options by detailed analysis of the community (small region) economic structure of the Grand Valley Trade Area (GVTA). A revised (scaled-down) input-output model of the upper mainstem subregion of the Colorado River Basin, reported by Udis and others [1973], was used to characterize economic interactions and levels of income and production for the three-county area of Delta, Montrose, and Mesa, which together define the West-Central Colorado GVTA (Figure 7). The base year of the model is 1970. A total of seven agricultural production sectors and 12 non-agricultural industries form the endogenous processing portion of this model. Local governments and households were also considered endogenous. State and federal governments, inventories, capital investment, and import-export accounts comprise the final demands or exogenous sectors. Sector definitions and classifications and an interpretation of the model are reported by Leathers [1976b]. The conventional input-output tables -- interindustry transactions, technical production coefficients, and direct and indirect coefficients -- are reproduced in the appendix of this report, tables 6, 7, and 8.

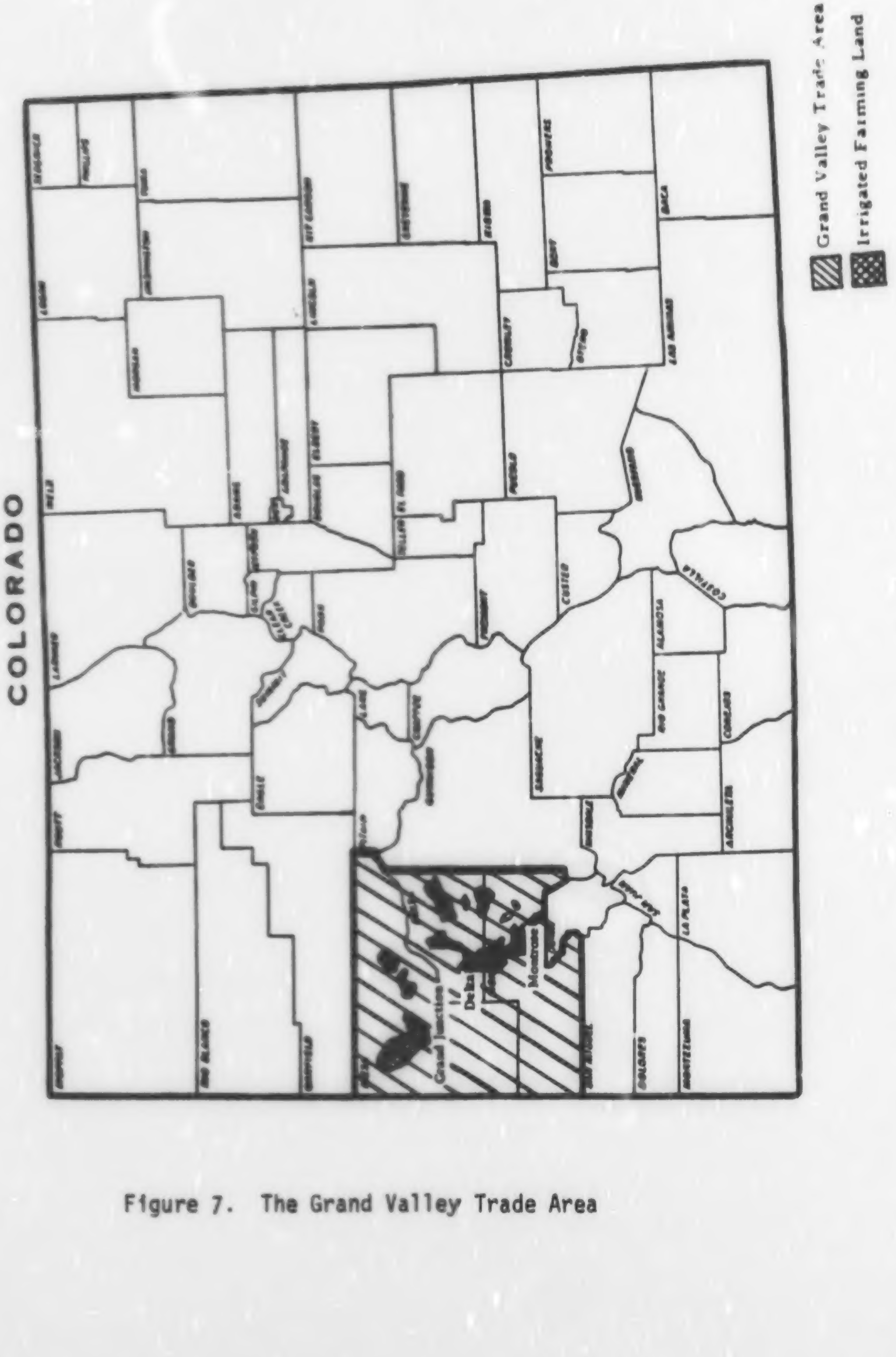

COLORADO
Grand Valley Trade Area
Irrigated Farming Land
Grand Junction
Delta
Montrose

Figure 7. The Grand Valley Trade Area

A number of modifications in conventional interindustry analysis techniques were necessary to satisfy the purposes of our study. First, given a small region (or community) orientation, our results consider only community impacts "as if" interregional (non-local) impacts, which result from interactions with the GVTA, didn't matter. This normally restrictive assumption is not a severe one here since trade flows between the GVTA and the rest of the state and regional economy are relatively insignificant for the field crop commodities in question.

Second, we define the household sector as after-tax return to locally invested capital, resident wages and profits. Accordingly, the adverse effects of crop acreage reductions are estimated internally "net" of state and federal taxes. Thus, our measure of income is, in effect, community value added rather than the more conventional form which measures before-tax (Keynesian) income effects.

Third, we omit the effects of forward linkages in estimating the direct and indirect impacts. The fed livestock and food processing sectors in the GVTA do not rely wholly upon locally grown produce; significant amounts of feed grains are imported by local feeders and grain handlers while some locally grown grains and forage are exported to other regions. Hence, sufficient imports to the GVTA to maintain current levels of output in the forward-linked industries is assumed. The sectorial income multipliers presented here are adjusted for backward linkages only, and relate to per dollar changes in output rather than per dollar changes in final demand (as conceptualized by Martin and Carter [1962]). We use the "adjusted" income multipliers to estimate adverse effects since it is the effect of a reduction in production on community income we wish to measure rather than the effect of a reduction in final demand. The scaled-down multipliers, which ranged from 90 to 99 percent of their unadjusted values, measure the change in regional wages, profits and returns to local capital per dollar change in crop revenue.

An interindustry model for the State of Colorado, recently reported by Gray, et al [1975], was used as a means of assessing the implications of land retirement in the Grand Valley on the State's economy. Forward linkages were also omitted in our use of this model to perform the indirect impact analysis.

Accounting Stance

We consider each land retirement option under each of two assumptions about accounting stance and resource mobility. This procedure permits the establishment of reasonable upper and lower bounds on the social costs of the program. An upper bound estimate of land retirement cost is obtained by computing the direct and indirect income effects via a regional accounting stance. Under this assumption capital, labor and entrepreneurial resources in both the agricultural production sectors and the related processing sectors are assumed to have only a limited opportunity for reemployment in productive activity elsewhere in the region. This limited resource mobility is reflected in an assumption that only 30 percent of such displaced persons and capital resources will be reemployed within a reasonably short time. This approach follows that of Kelso, et al [1974].

A national accounting stance and an assumption of instant and costless mobility of non-land resources provides a lower bound estimate on land retirement costs. This perspective implies that all labor and mobile capital resources employed in irrigated crop production (plus those affected in forward or backward linked sectors) can immediately be reemployed elsewhere in the national economy without loss of productivity. In essence, a national accounting perspective does not view secondary effects as legitimate economic consequences unless a full employment condition exists in the national economy.

C. RESULTS AND DISCUSSION

The findings of our analysis are reported in two subsections which follow: the first is devoted to a discussion of the local impact of retiring irrigated land in the GVTA, and the second considers the effect of reduced crop production on the Colorado economy.

Local Direct and Indirect Costs

The adverse effects of reduced crop production in the GVTA are summarized in Table 11. Annual direct and indirect costs, measured in terms of reduced community income, are estimated for the retirement Options I and II under a regional accounting stance. These costs are derived from sectorial income multipliers (shown in Appendix Tables 7 and 8) which are net of forward linkages. In this adjusted form, the multipliers measure direct, indirect (and induced) changes in household income per dollar change in output of the impacted crop sectors.

The forage and feed crops sector includes corn grain and silage, permanent pasture and alfalfa; sugar beets and small grains are handled in the food and field crop sector; and orchard and vegetable enterprises are represented in the fruit and specialty crop sector of the model. Since

TABLE 11. COMMUNITY INCOME REDUCTION UNDER TWO OPTIONS FOR RETIRING IRRIGATED LAND IN THE GRAND VALLEY TRADE AREA

Impacted Sectors	Total Acreage	Gross Income Per Acre[a/]	Sectorial Income Multipliers[b/]			Community Income Reduction in $1000[c/]			
			Direct	Indirect	Total	Direct	Indirect	Total	Nonrecoverable
OPTION I: RETIREMENT OF SELECTED LOW PRODUCTIVITY LANDS									
Forage and Feed Crops	6,050	$158.40	.4020	.4530	.8550	$385	434	819	574
Food and Field Crops	2,550	223.60	.5185	.4273	.9458	296	243	539	377
Totals	8,600	($177 ave.)				681	677	1,358	951
Annual Nonrecoverable Income Loss Per Acre: $110.23									
OPTION II: RETIREMENT OF ONE COMPLETE IRRIGATION SYSTEM (AVERAGE PRODUCTIVITY)									
Forage and Feed Crops	15,720	$275.40	.4020	.4530	.8550	$1,740	1,961	3,701	2,591
Food and Field Crops	4,510	537.96	.5185	.4273	.9458	1,258	1,037	2,295	1,606
Fruit and Specialty Crops	270	1,292.00	.3234	.5176	.8410	113	181	294	205
Totals	20,500	($349. ave.)				$3,111	3,179	6,290	4,402
Annual Nonrecoverable Income Loss Per Acre: $214.77									

---

a/ Sector gross income per acre (valued at 1975 prices) reflects a weighting of individual crops according to their proportion of the total acreage included in the sector aggregation.

b/ These multipliers, net of forward linkages, measure the change in household income (returns to local capital investment, wages and profits) per dollar of change in sector output (in this case gross revenue per acre).

c/ Columnentries are foundby multiplying the product of sector acreage and weighted gross income by the appropriate multiplier. Nonrecoverable income loss is total reduced community income less a recoverability factor of 30 percent.

orchard and other high value crops are rarely grown on poorer soils, the fruit and specialty crop sector is not considered under the first option.

Assuming a recoverability of displaced resources at 30 percent, a cutback in production involving 8,600 acres of poor quality soils in the Grand Valley would generate a net loss in community income of $951,000 annually. Under Option II, which retires 20,500 acres of average productivity, the loss is $4,402,000. On an annual per acre basis these income losses are approximately $110 and $215, respectively.

These costs are compared with our lower bound estimates (based on a national accounting stance) in terms of total program costs (part A) and cost effectiveness (part B) in Table 12. Total program costs reflect reduced income plus an additional charge for implementation and administration of the program. We estimate these charges at 10 percent of annual income losses. Since the amount of salts avoided by retiring selected irrigated croplands is not known with certainty, we "bracket" the provisional estimates for salt pickup per acre to demonstrate the sensitivity of this parameter to the cost effectiveness of the program.

In general, the incremental costs of salt removal (in $ per ton), using the provisional estimates of salt pickup, appear to be competitive with other more expensive controls such as canal lining. However, the cost effectiveness of the program is quite sensitive to assumptions regarding estimates of salts removed and accounting stance. Accordingly, it is important that these assumptions are considered very carefully in comparing alternative salinity control programs. For example, the cost of partial retirement (Option I lands) vary from $6.13 per ton to $14.30 per ton depending on the assumed rate of salt pickup per acre, and more

TABLE 12. SUMMARY OF ANNUAL REGIONAL COSTS AND COST EFFECTIVENESS: UPPER AND LOWER BOUND ESTIMATES FOR THE TWO LAND RETIREMENT OPTIONS

Measures and Options	Estimated Annual Costs (1975 Dollars)			
	Lower Bound[a]		Upper Bound[b]	
	Per Acre	Total	Per Acre	Total
A. PROGRAM COSTS[c]				
Partial Land Retirement, Option I:				
Income Reduction	39.00	335,400	110.23	951,000
Total Program Costs	42.90	368,940	121.25	1,046,100
Complete Land Retirement, Option II:				
Income Reduction	90.00	1,845,000	214.77	4,402,000
Total Program Costs	99.00	2,029,500	236.25	4,842,200

B. COST EFFECTIVENESS[d]

Salts Removed in Tons Per Acre	Dollars Per Tons	
	Lower Bound	Upper Bound
Partial Land Retirement, Option I:		
3	14.30	40.42
5.4	7.94	22.45
7	6.13	17.32
Complete Land Retirement, Option II:		
5	19.80	47.25
8.2	12.07	28.81
11	9.00	21.48

a/ Assumes a national accounting stance and perfect mobility of displaced resources; hence the costs reflect compensation payments to participating farmers as determined by income capitalization of long run earnings to irrigated farming.

b/ Assumes a regional (or local) accounting stance, 30 percent recoverability of displaced resources, and the absence of forward linkages. Costs are expressed in terms of reduced community income in response to the direct, indirect and induced effects of reduced production.

c/ Total program costs reflect additional charges for implementation and administration which are assumed at 10 percent of reduced income.

d/ Estimated annual costs per acre divided by the indicated rates of salts removed in tons per acre.

than double if a regional accounting stance is assumed. We believe the regional accounting stance, however, provides a fairly generous upper bound on total program costs.

Implications for the State of Colorado

The impact of reduced production of irrigated crops in the Grand Valley on the State's economy was evaluated with the use of the State input-output developed by Gray and others [1975]. This model is also constructed on a 1970 data base. As with the GVTA model, the income multiplier was adjusted for forward linkage effects. Further, we assume 30 percent recoverability of persons and resources displaced by the program, and a 10 percent additional cost to account for the expense of implementation and administration. Given these procedures, our estimates of State impacts are directly comparable with the upper bound "local" impacts reported in Table 12.

The income reduction effect of retiring cropland in the Grand Valley (Options I and II) is apparently not as severe on the State economy as it might be for the economy of the small region. The reason for this is attributed to the difference in size of the adjusted income multipliers. Referring again to Table 11, the GVTA sectorial multipliers for the impacted crop sectors were shown to have a magnitude of about .8 or .9. Under similar assumptions, the State multiplier for irrigated agriculture (in which case all irrigated crops are lumped together) is .4304 or about half that of the small region multipliers. Accordingly, the program costs to the State would be about half the upper bound costs reported in part A, Table 12.

The smaller multiplier effect at the State level is attributed to some of the differences observed between the two regions. Irrigated agriculture plays a more prominant role in the economic structure of the GVTA as compared to the State economy. Also, because orchard enterprises and small farms tend to be more labor intensive, smaller farms and specialty crop enterprises common to the GVTA are not typical of the State as a whole. However, a careful study of this particular aspect of the problem was considered to be outside the scope of our analysis. A detailed analysis of State consequences would probably require less aggregation of the agricultural sectors, but more importantly, would involve a careful specification of alternative cost-sharing schemes between the State, the impacted area, and the federal government.

D. SUMMARY OF COST-EFFECTIVENESS

The purpose of this chapter has been to estimate the economic consequences and cost effectiveness of land retirement as a means of reducing irrigation-induced salinity in the Grand Valley. Land retirement is obviously a drastic salinity control measure. Nonetheless, a cut-back in irrigated farming in many areas of the Upper Colorado River Basin is the only sure way that significant amounts of salts can be removed from the river system. As the Upper Basin States continue to develop their respective rights to Colorado river water, hence unavoidably add to the rivers' salt load, each State is responsible for enacting procedures for removal of salts in order to insure that the 1972 water quality standards (which apply at the State boundaries) are not exceeded [U. S. Environmental Protection Agency, 1975]. In effect this trade-off between present and future uses may well involve land retirement schemes if alternative control measures prove ineffectual or become relatively more expensive in the future.

Table 13. ESTIMATED INCREMENTAL COSTS OF SALT REMOVAL FOR PROPOSED ALTERNATIVE CONTROL MEASURES, GRAND VALLEY, COLORADO (1975 dollars)

Control Measure	RANGE IN ESTIMATES Annual Salt Discharge Avoided (tons)	Average Cost ($ per ton)
Modified Irrigation Practices[a/]	50,000 - 100,000	3.42 - 1.71
Aluminum Pipes for On-Farm Conveyance and Irrigation[b/]	75,000 - 150,000	14.15 - 7.07
Lining of Main Canals[c/] and Laterals	200,000	32.72
Drainage Modifications	- - unknown - -	
Desalting Saline Ground Waters[d/]		
Partial Land Retirement, Option I[e/]		
Lower Bound	25,800 - 60,200	14.30 - 6.13
Upper Bound	25,800 - 60,200	40.42 - 17.32
Complete Land Retirement, Option II[e/]		
Lower Bound	102,500 - 225,500	19.80 - 9.00
Upper Bound	102,500 - 225,500	47.25 - 21.48

[a/] Based on an annual water delivery of 215,000 acre feet, Table 9 (section IV).

[b/] Refer to table 10, section IV.

[c/] Adapted from [U. S. Bureau of Reclamation, 1976]

[d/] Adapted from [Walker, 1976]

[e/] Refer to table 12.

With the aid of a small-region input-output model of the Grand Valley Trade Area (GVTA), local community impacts were estimated for two types of retirement programs. The options considered were: (1) withdrawal of water supplies from 8,600 acres of less-productive soils in the Valley -- a "partial" retirement scheme; and (2) the phasing out of an entire irrigation district of about 20,500 acres of average productivity soils -- a "complete" retirement scheme. Under both Options withdrawal of irrigation water means termination of all crop production on these acreages. This would also hold true for much of the irrigated lands in the Upper Basin outside Colorado. A second input-output model, representing the economy of Colorado, was used to estimate the probable impacts on the State of reduced crop production in the Grand Valley.

The results of our analysis, given a number of assumptions which provide upper and lower bounds on our estimates, show land retirement to be competitive with some of the more expensive structural controls under consideration in the Grand Valley and elsewhere (Table 13). These include desalting, drainage improvements and canal lining, the costs of which appear to be above $30 per ton of salts removed. Depending upon the nature of assumptions used to derive the cost effectiveness of land retirement, we have shown that the incremental cost vary over a wide range -- from less then $7 per ton to over $40 per ton. However, owing to the way in which the upper bound estimates are calculated, we feel they represent a generous approximation of the full economic costs of the program.

In closing, we wish to stress the limitations of our analysis, particularly with regard to the precision of our knowledge of the sources and mechanisms of salt pickup in the Grand Valley and of those "social" costs of the program which cannot be evaluated through the market mechanism. Further, we have not considered monitoring and enforcement costs directly, except to the extent that our estimates were inflated by 10 percent to approximate the overall costs of administering the program. This assumption may prove to be an oversimplification of a very difficult and costly problem for the enforcing public agency.

Although conceptual disagreement concerning measure of downstream benefits (damages avoided) are not resolved, it is our judgment that such benefits are not large enough to warrant undertaking of any of the proposals other than adjustment in on-farm water management. We are dubious about even this alternative because of uncertainties involved in measuring the hydro-salinity relationships. Where the market system is being by-passed to serve some presumably over-riding public interest, it is desirable to include in the public programs some incentives to help assure an efficient allocation of resources. In this case, we would suggest that at least a half share of the burden of improving water quality be borne by the water user groups in the Lower Basin. If such a plan were adopted we would be more certain of that region's real need for reduced salinity.

SECTION VI

RETURN FLOW SALINITY MECHANISMS: A REAPPRAISAL OF ESTIMATES AND ASSUMPTIONS

A. INTRODUCTION

In the preceding sections, which dealt with the costs of alternative salinity control programs, it was shown that cost-effectiveness (the relative marginal costs) is very sensitive to assumptions about the quantity of salts removed by such programs. This is most notably demonstrated by the fact that structural and land retirement measures are "borderline", even under generous assumptions, in terms of national (or regional) efficiency benefits. Since these programs can only be implemented at very high costs to taxpayers, it seems useful at this point to reconsider some of the assumptions upon which the proposed programs are predicated; and, for the most part, this involves reevaluating the "physical" rather than the economic aspects of the problem.

In this section, the fundamental propositions and empirical evidence which supports the need for public intervention in the Grand Valley for the purpose of controlling salinity are questioned. Beginning with the early investigations in the Valley, the results of significant "macro" and "micro-level" efforts are compared and their implications discussed (Part B). An alternative research methodology, formulated in Part C, proposes that least-squares regression analysis of historical time series data is an appropriate approach with which to test the competing hypotheses, and to suggest areas of research which require more critical examination. The results of the regression analyses are reported in Part D, and the implications and limitations of the study are summaried in Part E.

B. REVIEW OF PREVIOUS RESEARCH

It is well known that increased water salinity (dissolved solids) is attributable to both natural and manmade causes, but the extent to which each contributes to the total salinity load in a particular situation is often difficult to discern. This difficulty arises because of the complex, variable nature of many different processes which occur simultaneously within the hydro-geologic-salinity system. Unfortunately only the manmade causes are amenable to control in many actual situations. Therefore, a valid economic assessment of alternative control measures for agricultural and other manmade sources depends in large part upon our ability to separate them from natural processes.

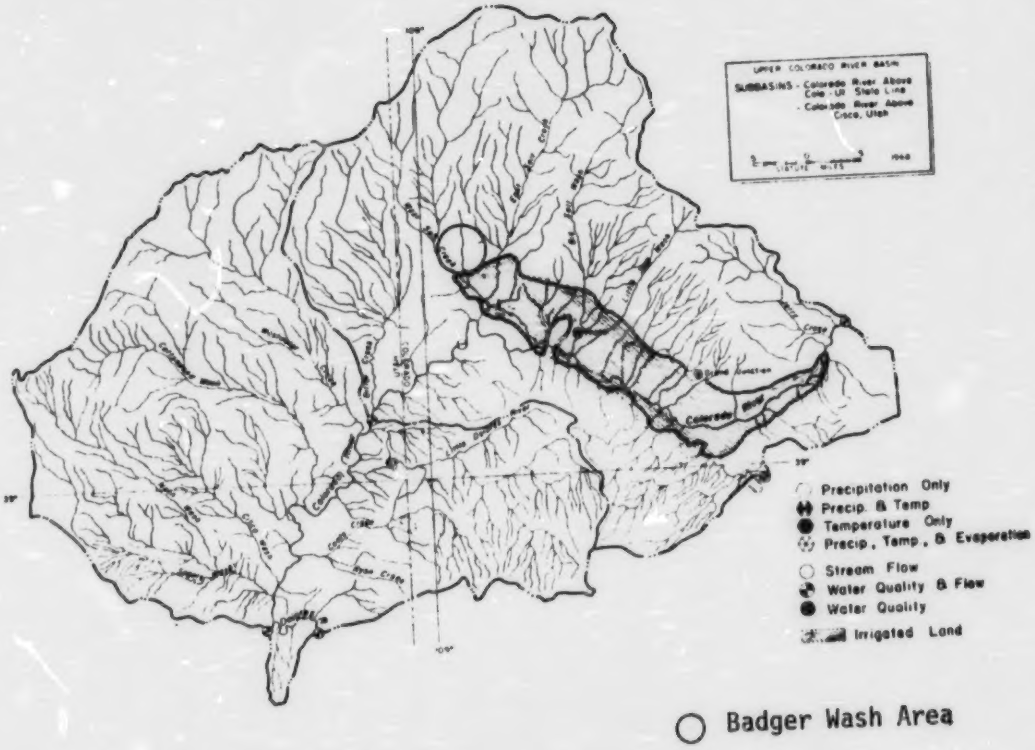
The first comprehensive study of this problem was conducted during the mid sixties [Iorns *et al*., 1965]. In that study detailed analyses of separate subbasins within the Colorado River Basin were made to identify the sources of salt loading and to determine the relative magnitude of each contribution. Input-output budgeting techniques were used to estimate average monthly changes in flows and salt loads covering a period from 1914 to 1957. A second study, using a similar methodology but more comprehensive in scope, was concluded shortly thereafter [Environmental Protection Agency, 1971]. This study was based on monthly input-output data collected during a one-year period, June 1965 to May 1966. Because of limited time and resources, most of the agency's monitoring effort was concentrated in the upper basin. Further, no attempt was made to distinguish between salt "loading" and "concentrating" effects.

The results of the EPA study strongly implicate irrigated agriculture as a major manmade contributor to the River's salinity. The EPA report concluded that salt loading as a consequence of irrigation accounted for 37 percent of the total salt load in the upper basin. Natural runoff was the largest source, accounting for 52 percent of the total load, while natural point sources (highly mineralized springs) and municipal-industrial sources explained the balance (9 and 2 percent, respectively). The Grand Valley area and the Gunnison River subbasin, both in Western Colorado, were found to be particularly significant agricultural sources representing 50 percent of the upper basin's agricultural contribution.

In the Grand Valley reach, an area extending from Cameo to below Fruita (see figure 8), the average annual salt pickup was estimated at 700,000 tons. Of this, EPA estimated that 93 percent was the consequence of irrigation return flow. Less than 5 percent of the total was attributed to natural runoff. The conclusions of Iorns, et al. [1965] were substantially the same with regard to proportion from irrigation, although the average pickup in the reach was estimated at about 500,000 tons. Because of the broad orientation of both studies, no detailed analyses of specific pickup mechanisms for either agricultural or natural runoff contributions were attempted.

Agricultural Pickup Mechanisms

Return flows from an irrigated area, defined as that portion of water diverted for irrigation which eventually returns to the stream, tend to increase the total dissolved solids load carried by that stream. Often included in the dissolved solids load are quantities of nitrates, phosphates and nondegradable chemicals which are used on the irrigated lands. Since conventional treatment methods are normally ineffectual in removing these constituents from return flows, agricultural use may impose serious problems for other downstream users.


UPPER COLORADO RIVER BASIN
SUBBASINS - Colorado River Above Colo - Ut State Line
- Colorado River Above Cisco, Utah
STATUTE MILES
1968
COLORADO
UTAH
Grand Junction
Colorado River
Precipitation Only
Precip. & Temp
Temperature Only
Precip., Temp., & Evaporation
Stream Flow
Water Quality & Flow
Water Quality
Irrigated Land
Badger Wash Area

Source: Hyatt, et al [1970]

Figure 8. Grand Valley Reach of the Colorado River

The quantity of water that ultimately returns to the stream system is influenced by a number of factors: canal and lateral seepage, soil water holding capacity and infiltration characteristics, precipitation, cropping pattern evapotranspiration rates, and irrigation practices. The quality of return flows are also affected by many of these same factors. In general, the quality of return flows depend upon the time and the extent to which the water is in contact with salt bearing surfaces. Waters which receive minimal exposure to soil surfaces will pick up comparatively less salts than waters exposed to large soil surface areas for long periods of time. Similarily, waters which penetrate below the root zone of growing crops have greater opportunity to interface ground waters below irrigated lands which frequently contain high dissolved mineral concentrations. This problem is particularly acute in the Grand Valley, and is believed to be fairly common elsewhere in the upper basin [EPA, 1971]. These phenomena, coupled with the concentrating effect of evapotranspiration, can produce concentrations of salts in the soil solution up to 10 times that of the irrigation water at the point of diversion [Bishop and Peterson, 1969].

Under normal circumstances if irrigation diversions are high in relation to evapotranspiration requirements (a condition which typically exists early and late in the growing season), rates of return flow are high, and salinity concentration in the subsurface components of return flow (deep percolation and seepage) are usually low. This is largely due to the high proportion of surface runoff in the total return flow and the relatively short period of time surface waters are in contact with soils. On the other hand as evapotranspiration requirements rise relative to stream diversions (normally mid-summer conditions), salinity concentrations in return flow tend to increase. Most authorities believe, however, that the total rate of salt outflow from an irrigated system is greater under higher irrigation applications than for low application rates [Hyatt, 1970].

Skogerboe and others [1974] have conducted extensive investigations of return flow salinity in the Grand Valley as a followup to the earlier studies. They applied a similar input-output methodology, but incorporated detailed submodels of specific pickup mechanisms emphasizing the components of return flow waters. Using monitoring instruments to measure surface and groundwater flows and salinity concentrations at a field site east of Grand Junction, they were able to calibrate a hydrosalinity budgeting model which they compared to the total Valley input-output data for the 1968 water year. Their results indicate that seepage losses in main canals and laterals can account for about 55 percent of the total salt picked up in the Grand Valley reach. The balance (45 percent) was attributed to deep percolation losses that occur as a result of inefficient irrigation practices. Surface return flows (field tail water and canal spillage) were not found to be significant sources, and natural runoff was not accounted for in their model.

The mechanism by which subsurface return flow waters (deep percolation and seepage losses) pick up salt is thought to be explained by a displacement process. Deep percolating waters recharge the aquifers which underlie protions of the irrigated lands, and the hydrostatic head created displaces some saline ground water (as high as 10,000 ppm) out of the aquifer and into the river [Skogerboe and Walker, 1972]. As a means to control salt pickup in the Valley these researchers have studied improved irrigation practices, canal and lateral lining, and drainage systems -- all designed to reduce or remove deep percolating waters before coming in contact with the water table.

The results of experiments conducted by the Agricultural Research Service as a site west of Grand Junction are not consistent with those of Skogerboe and others [Kruse, 1975]. These researchers have found that conveyance system seepage losses alone could account for nearly all of the salt pickup in the study reach. Kruse and his associates found relatively impermeable soils and low infiltration rates. Their study of irrigation practices therefore concludes that deep percolation losses from irrigation are apparently quite small, hence this mechanism of salt pickup may not be as important as earlier hypothesized. Accordingly, the control measure most likely to be effective would be canal lining, since measures to improve on-farm irrigation efficiency would probably not yield significant reductions in salinity.

Natural Pickup Mechanisms

Water quality of the upper Colroado River Basin is profoundly influenced by the geology of that area. Large portions of the area are underlain by the Mancos shale of Late Cretaceous age and by other ancient formations with similar physical and chemical properties [Iorns et al., 1964, 65]. Distinctive landforms have resulted from erosion of these formations, and as a result rock and residual materials have been carried away leaving an extensive network of natural washes, plateaus, steep canyons, and sparse vegetation. The contact of water with the saline geologic formations, either from natural precipitation or from irrigation, causes a serious degredation of water quality in streams receiving runoff or drainage waters.

In the higher reaches of the watershed where much of the basin's water supply originates, a continuous interchange between surface waters (snow melt and overland runoff) and groundwaters occurs. During this process, rock and residual materials react with the water and impart to it chemical constitutents which are characteristic of the watershed geology. When waters of differing constituents are mixed chemcial reactions normally take place. These reactions can cause either a loss in constituents via precipitation or an increase as new salts are dissolved. Similarily, when an aquifer receives a direct recharge, the outflow of the aquifer is indicative of the chemical makeup of the alluvium through which the water has passed.

Within the subbasins of the upper Colorado River Basin influent pnenomenon typically exist at the higher elevations while effluent flows predominate in the lower reaches of most tributaries [Iorns, _et_ _al_., 1964]. An influent stream is one which adds to a ground water system whereas an effluent one intersects the water table and allows groundwaters to surface. Most perennial streams are effluent over a portion of their length, and the existance of both conditions in a single reach is common [Linsley, _et_ _al_., 1958].

Waters passing through alluvium as influent flow eventually return to the mainstream channel. Within a particular subbasin the amount of interchange between surface and groundwaters may be influenced by water levels in the channel itself. This specific mechanism, namely the "interchange hypothesis" as Hyatt has chosen to call it, has not received careful study in the Grand Valley subbasin, but may be a significant salt pickup mechanism [Hyatt _et_ _al_., 1970].

During periods of high stream flow (which normally occur during the runoff season in late spring, but may also occur after severe thunder showers in the late summer) some increase in interchange waters would be expected. Since dissolved solids content of groundwater is usually higher than that of surface waters, a mixing of the two will generally cause an increase in the salt load of surface waters. The quality of surface waters in the upper Colorado River Basin exhibit (over a period of years) wide variations, and because groundwaters of this area tend to be quite salty, it seems plausible the interchange hypothesis can account for significant increases in salt loads at the outlet of a subbasin. Studies by the U. S. Bureau of Reclamation [1967] indicate that along certain reaches of the Colorado River there are large increases in the salt load which cannot be attributable to the agricultural system.

Increased salt loads can be expected to be particularly significant in mildly sloping valleys underlain by large, permeable alluvia. The fact that these same features also characterize irrigated agricultural areas apparently has fostered the belief that any incremental salt loads added to the stream which traverses such valleys are largely the result of irrigation (e.g., "for the Grand Valley area the unbudgeted increase in dissolved-solids load...at least 440,000 tons per year...may be attributable to irrigation." (Iorns _et al._,[1964]). Because it is a natural phenomenon, Hyatt suggests that the interchange hypothesis explains salinity increases which occur even during periods of the year when return flows from agricultural lands are insignificant.

Hyatt and others [1970] constructed an analog simulation model of the upper basin to test a number of alternative hypothesis about natural and manmade salt pickup mechanisms. Essentially the same watershed areas were studied as described in the EPA and Iorns reports. Specific pickup mechanisms were analyzed on the basis of historical hydrosalinity relationships estimated from available secondary data on stream discharge, diversions, climatic conditions, and water quality. With few exceptions the results indicated significant interchange processes, especially for subbasins with irrigated lands. The computed mass rate of salt flow leaving each subbasin, before interchange was introduced, was found to be much less than the measured rate of salt outflow, often from one-half to one-tenth of the actual values recorded at U.S.G.S. gaging stations. The implication of their findings is that the earlier studies overestimated agricultural contributions and underestimated natural ones. For the Grand Valley area and the Gunnison river subbasin, they estimate that salt loading by natural processes (including interchange) possibly exceeds agricultural sources in magnitude of salt pickup.

Most authorities have discounted the possibility that surface runoff from snowmelt and rainfall is an important salt pickup mechanism in the Grand Valley reach. Consequently, surface runoff mechanisms in the area have received little study, and their contribution to salt loading is unclear. At a research site (Badger Wash) located northwest of Grand Junction, researchers with the U. S. Geological Survey have studied salt loading from surface runoff as part of a more general investigation of erosion processes [Schumm and Lusbey, 1963]. Schumm found that seasonal changes in soil characteristics (the lithosols) are great enough to affect both the rates of erosion and the erosion process itself. Based upon analyses of seven years of storm data, runoff was much greater in late summer and fall for storms of comparable inetnsity, and the average runoff and the ratio of runoff to precipitation were consistently larger for all sizes of storms during this period. Unfortunately the amounts of dissolved solids carried away by runoff water was not carefully documented in these early experiments. But as a result of these findings, it is reasonable to hypothesize that the majority of salt loading which occurs from surface runoff likely takes place during the late summer and fall months of the year.

Hadley [1976], reporting on more recent results from studies at Badger Wash, estimates natural runoff at 2 to 3 times that reported by the Environmental Protection Agency [1971] and Iorns et al. [1964] for this reach of the river. Soil Conservation Service estimates, based on recent analyses of sediment samples taken above the irrigated lands at the base of the Bookcliffs (see figure 1) and farther west, concur with Hadley's conclusions [Elkin, 1976] . Elkin estimates the average annual salt yield at 80,500 tons for a runoff area of approximately 1,370 square miles, or 59 tons per square mile of surface area compared to 18 tons by EPA estimates. Clearly, these divergent conclusions warrant further study of this aspect of the problem.

Implications for Policy Decisions

In most scientific disciplines the results of research tend to raise more questions than answers. The divergent opinions which surround the question of how to control salinity in the Grand Valley probably result from the complex nature of the problem rather than from faulty analyses. However, it may be useful to summarize the methodological procedures discussed above in terms of an alternative approach, and to consider briefly some of the policy implications which obtain.

The simulation approach, which has been used extensively in the Grand Valley and elsewhere in the Colorado River Basin, is essentially a detailed input-output budgeting procedure. Structural coefficients within these models represent an aggregation of the many separate processes which occur in the hydro-geologic-salinity system and are typically estimated from historical data when it is available. The estimated models are then "calibrated" to a base year or other reference period. Calibration involves comparing the model outputs with the reference period data and adjusting the parameters until a suitable correlation is obtained. Once calibrated the model is said to be representative of the physical system being studied, i.e., for the reference period. In the case of hydro-salinity systems the simulation approach should be regarded as "partial" analysis since it is normally used to represent the base year or reference period and not the period of years which may comprise the data base. Thus, the appropriateness of the model for describing salt pickup mechanisms and magnitudes of salts added to a water course is uniquely tied to the reference year. Given cyclic and/or stochastic phenomena, a reference year selected at random may be quite unrepresentative as a predictor of historical or future trends. Perhaps this explains some of the discrepancies in research findings.

Least-squares regression is an alternative analytical technique to the simulation (budgeting) approach. Regression techniques, sometimes used for estimating the structural parameters of simulation models, are specifically designed to perform statistical tests on the functional relationships among specified variables. An advantage of regression analysis is that time-trend data (including stochastic processes)can be carefully evaluated. In most instances this is not done with conventional input-output budgeting techniques. In fact, this study is believed to be the first attempt to use regression methods and time series analyses to describe salt pickup mechanisms in the Colorado River Basin.

The divergent research findings reported by many of the state and federal agencies and private commissions having become involved with the salinity problem pose an interesting dilemma for policy makers. On the one hand there is a sense that action on the problem is urgent, while on the other hand, they face a high degree of uncertainty as to cost effectiveness in choosing among different control measures.

C. METHODS OF ANALYSIS AND DATA SELECTION

Many important problems in the social, biological and physical sciences involve measurements in time. In fact, most information we have about the real world only exists in the form of time series records of events or "variables". Controlled experiments involving the study of these variables are expensive, time-consuming, and in some cases, impossible. For this reason, the place of statistical analysis in scientific research is well established.

Statistics provide a means of measuring the elements involved in relationships and in examining the relationships themselves, but it does not itself furnish an explanation of the phenomenon under examination. The effort to form hypotheses as a mathematical model of actual processes, and to reduce the variables under study to succinct numerical statements, forces the investigator to approach his problem more clearly and logically. However, statistical analysis is not a substitute for careful thinking; it is, as best stated by Ezekiel [1959], "....an aid which may make that thought and skill even more productive of worthwhile results".

The Techniques of Correlation and Regression

In any system in which variable quantities change, it is often necessary to examine the effects that some variables exert on others in order to gain insights into the functioning of the system. This is especially important in the study of natural systems where actual functional relationships are too complicated to understand or to describe in complete detail. The statistical techniques of correlation and regression are useful methods whereby complicated natural processes can be reduced to simple mathematical equations based on the testing of hypothesized relationships between appropriate variables [Draper and Smith, 1966].

Correlation and regression analyses are a means to understanding the nature of association between two (or more)variables; correlation is a measure of linear relation and indicates whether two variables are positively or negatively related, whereas regression is applied to specific functional forms among two or more variables that can be either linear or nonlinear. Although neither technique claims to identify cause and effect relationships, in regression analysis hypotheses are set up to confirm whether or not variable X has an "influence" on variable Y. In multiple regression, the influence of more than one independent variable (X's) on the dependent variable (Y) can be jointly evaluated. Important test statistics in regression analysis relate to (1) the significance of the estimated equation parameters (regression coefficients), which facilitate tests of the strength of the hypothesized associations; and (2) the significance of regression equations themselves (the proportion of total variation in the dependent variable associated with the variation in the independent variable(s) in a specified functional relationship).

Data Sources and Evaluation

The data base for this analysis was compiled largely from secondary sources. Information selected for careful study was limited to the natural runoff and irrigation sources of salinity; industrial and municipal contributions and natural point sources were not examined independently due to time and resource limitations. A time series of monthly data, covering a 22-year period (1951 through 1972) was obtained on stream flows, total dissolved solids concentrations, the disposition of waters diverted for irrigation, cropping patterns, precipitation and evapotranspiration in the study area. Although much longer records are available for some of these data, the period of study chosen represents a consistent set of actual observations, thus avoiding the necessity for extrapolation or use of synthetic data.

Stream Flow and Salinity

The only permanent, systematic record of water flow and quality available for the reach is maintained by the U. S. Geological Survey [1973]. Measurements of surface flow are recorded on a daily basis at each permanent gaging station whereas complete water quality analyses are typically performed two or three times each month. The water quality analysis includes measurement of specific conductance, temperature, turbidity, alkalinity, and differentiates specific ionic concentrations or nonconservative constituents. The water quality parameter selected as the dependent variable in this study was total dissolved solids (TDS) in tons per unit time.

The salt load carried by inflow and outflow waters was estimated by multiplying TDS concentrations (tons per acre foot) and flows (acre feet). Tons per acre foot indicates the dry weight of dissolved solids in one acre foot of water, and is computed by multiplying the concentration in milligrams per liter by 0.00136. Since water quality samples were taken most consistently on or near the 20th of each month, the sample concentration nearest the 20th was used in computing the average monthly salt load at each station location. Monthly net salt pickup for the reach (S_{it}) was calculated by subtracting the computed values at each inflow station from the reach outlet station value (equation 1). The annual estimates of net salt pickup for the reach (S_t) are the sum of the monthly estimates, and therefore reflect a weighted average of monthly flow rates and TDS concentrations (equation [2]).

$$[1] \qquad S_{it} = [S_u - (S_c+S_g+S_d)]_{it}$$

$$[2] \qquad S_t = \sum_{i=1}^{12} S_{it}$$

where: S = net salt load in tons

i = month of year, i = 1, 2, ...12

t = year in times series, t = 1, 2, ...T

Location of sampling stations

u = Colorado River near Cisco, Utah (reach outlet)

c = Colorado River at Cameo, Colorado (inflow)

g = Gunnison River at Grand Junction, Colorado (inflow)

d = Dolores River near Cisco, Utah (inflow)

An equivalent procedure was used to derive net river discharge (F_{it}), i.e., the net gain or loss in flow for the study reach.

Due to rather large variations in flow and concentration of salts which can occur over a period of 30 days, the above procedure could yield inaccurate measurements of monthly salt pickup. For example, if the TDS concentration on the 20th of the month is 30 percent below the "true" weighted average, our estimate of the salt load will also be 30 percent below its true value. Similarily, an error made in estimating the salt load at one of the four station locations will cause an error in computing the net pickup for the reach. Errors in measurement are indicated by a number of "outlyers" in the data, because a fairly small sample size was used (22 years). This presents problems for estimating statistical parameters. The implications of this in interpreting the results of the analysis is discussed in detail in a later section.

Hydrologic systems are characterized by stochastic processes (including possibly cyclic behavior), hence a significant bias could be introduced by the particular interval of observations selected for analysis. As an illustration, the mean flow and salt load for the Grand Valley reach, computed from three different intervals of time, are compared in Table 14. These computations suggest stream flows have apparently declined during the entire period while the net average salt load rose in the second interval and fell in the third. The magnitude of mean salt loads for two of the three intervals is substantially lower than the generally accepted long term average of 600,000 tons [U. S. Bureau of Reclamation, 1975]. The fact that the mean values are different suggests the possibility that time trends or cycles exist and should be considered in a careful analysis of salinity cause and effect.

TABLE 14 MEAN SALT LOADS, STREAM FLOWS, AND TDS CONCENTRATIONS IN THE STUDY REACH: A COMPARISON OF THREE TIME INTERVALS

Location of sampling stations in the study reach	Annual Mean Values for Three Periods of Water Flow and Quality[a]								
	1914-1957[b]			1943-1960[c]			1951-1972[d]		
	Flow	Conc.	TDS	Flow	Conc.	TDS	Flow	Conc.	TDS
Colo. River, Cameo	2,998	.53	1,578	2,859	.54	1,537	2,656	.57	1,525
Plateau Creek, Cameo	170	.39	66	165	.41	68	(159)	(.43)	(68)
Gunnison River, Grand Junction	1,884	.81	1,519	1,705	.84	1,430	1,594	.87	1,383
Dolores River, Cisco	681	.68	460	(581)	.83	491	480	.96	462
Colo. River, Cisco	5,534	.74	4,120	5,030	.82	4,133	4,546	.86	3,922
Net Change[e]	-199	---	497	-280	---	607	-343	---	484

[a] Flows are measured in 1000 acre feet, concentrations in tons TDS per acre foot, and salt loads (TDS) in 1000 tons.

[b] Adapted from Iorns, et al [1965].

[c] U. S. Department of Agriculture [1965]. The number in parenthesis was not given in the report cited, but was supplied by the author.

[d] Summarized from published records, U. S. Geological Survey [1973]. The estimates in parentheses are extrapolations made by the author from incomplete historical records.

[e] Cisco data less the sum of the other stations.

Natural Runoff

Estimating the salt loading effects of natural-diffuse surface sources is complicated by the fact that natural washes and intermittent streams which transport salts to the main stream channel are ungaged and only periodically sampled. In the absence of direct observation, precipitation data was used as an indirect measure of surface runoff (or salt pickup). Records of monthly rainfall were obtained for three different locations within the study area [U. S. Department of Commerce, 1972]. Three weather stations, located at Grand Junction, Fruita, and near Cisco, were used in order to account for the possible effects of the spatial distribution in rainfall patterns.

The relationship between monthly or seasonal rainfall and rates of surface runoff is fairly well grounded on empirical evidence [Musgrave, 1947; Thomas and Benson, 1972; and Flaxman, 1972]. Although the actual process of salt pickup takes place on a day-to-day basis, depending upon (1) the frequency of storms, (2) rainfall amount and intensity, (3) surface vegetation and slope, and (4) soil salinity, infiltration, antecedent moisture, etc., Schumm [1963] has shown that the magnitude of runoff is closely associated with variations in seasonal precipitation. The data summarized in Table 15 illustrate the frequency with which storms of different sizes occur, and the seasonal effects on the precipitation-runoff ratio for the Badger Wash area(which can be located in figure 1). Both storm frequencies and precipitation-runoff ratios are clearly greater during the fall months, and according to our hypothesis, the same should be true of salt pickup from this source.

An alternative measure of natural runoff is net river discharge since ungaged overland flow must obviously be reflected in this variable. If

TABLE 15. SPRING AND FALL PRECIPITATION AND RUNOFF AT BADGER WASH, 1954 - 1961[a]

Range of Precipitation per Storm	Number of Storms		Average Runoff per Storm		Runoff-Precipitation Ratio	
	Spring	Fall	Spring	Fall	Spring	Fall
-(Inches)-			---(Inches)---			
.10-.20	13	23	.001	.008	.007	.050
.21-.30	4	11	0	.039	0	.145
.31-.40	3	11	.007	.063	.022	.185
.41-.50	3	7	.020	.093	.043	.198
.51-.60	1	2	.120	.180	.207	.322
.61-.70	1	4	.004	.290	.006	.440
.71-1.00	0	2	0	.380	0	.400
1.01-1.40	0	1	0	.470	0	.350
All storms	25	61	.004	.079	.015	.232

Source: Schumm, S. A. and G. C. Lusby. "Seasonal Variation of Infiltration Capacity and Runoff on Hillslopes in Western Colorado," Journal of Geophysical Research, Vol. 68, No. 12, June, 1963.

[a] Spring and Fall precipitation periods include the months of April through June and August through October, respectively.

the gaged stream flows are reasonably accurate for the study reach, then net discharge (F_t) will also act as a proxy for salt pickup in surface runoff.

Irrigation Return Flows

Irrigation was first practiced in the Grand Valley in the early 1880's, and by the late 1920's land under irrigation probably exceeded 75,000 acres. Since that time certain portions of the Valley have been retired from production as a consequence of problems encountered with waterlogging and a buildup of surface salts [Robinson, 1972]. At present approximately 56,000 acres are irrigated.

Colorado River water is diverted for irrigation by four irrigation entities: the Grand Valley Irrigation Company, the Grand Valley Water Users Association (a federal project), the Palisade Irrigation District and the Mesa County Irrigation District. A small amount of water is diverted from the Gunnison River by the Redlands Light and Power Company for irrigation south of the Colorado River (figure 8). For an average water year total Colorado River diversions have been estimated at 550,000 acre feet, nearly 10 acre feet per irrigated acre in the Valley [Skogerboe et al., 1974]. About half of this amount is actually delivered to farms, and of that delivered only about 3 acre feet per acre is typically needed to satisfy crop evapotranspiration and leaching requirements.

Because of the hypothesized significant effect of irrigation on the salinity flow system of the Grand Valley reach, return flow processes were defined as accurately as possible. Data sources and procedures used to measure the principal components, both subsurface (deep percolation and seepage) and surface (waste and field tail water), are described in the subsections which follow.

Canal Diversions. The time distribution and quantities of water diverted from the river and conveyed to the irrigated land area is fundamental to this analysis, since estimates of conveyence losses and irrigation waste water are derived from these statistics. Data on major canal diversions is available through the office of the State Engineer, but in consultation on the matter it was learned that in many cases only partial records are available for all diversions on a monthly basis. Accordingly, the approach followed in describing the history of diversions for the Grand Valley was to use available records for selected canals in the area thought to be representative of the total system.

The Government Highline Canal, managed by the Bureau of Reclamation, was selected as the "representative" canal system in the Valley. This canal services about 38 percent of the Valley's irrigated acreage and handles about 36 percent of total river diversions [Skogerboe, et al, 1974]. The data were obtained from annual summary reports prepared by the project office personnel in Grand Junction [Klapwyk, 1974]. Since the records maintained on this canal are historically complete and believed to be the most accurate of the four main canal systems, it was not necessary to extrapolate or extend the data to cover missing observations.

Seepage from Canals and Laterals. Numerous experimental observations are available on rates of seepage and the amount of seepage loss for most lateral and canal supply systems in the Valley [Kruse, 1975], but little or no information is available on the time distribution of monthly or annual seepage loss. The only source of data (known to the author) upon which limited inferences can be made is an annual published report of monthly water distribution statistics [Bureau of Reclamation, 1974].

Because of some discrepancies found between the published version and the actual field reports submitted to the regional office, the project office field records were selected for use [Klapwyk, 1974].

In these annual summaries estimates of seepage loss, in acre feet per month, are computed using a simple accounting procedure: river diversions (RD_{it}) less gaged deliveries to the lateral system (LD_{it}) and gaged spillage losses (Wc_{it}) yield unexplained residual water quantities (SLc_{it}) which are attributed to canal seepage losses (equation3). Lateral seepage loss (SLl_{it}) is estimated by subtracting from the lateral supply the amount delivered to farms (FD_{it}) and the amount spilled (Wl_{it}) to maintain an appropriate system flow (equation 4).

$$[3] \quad SLc_{it} = RD_{it} - (LD + Wc)_{it}$$

$$[4] \quad SLl_{it} = LD_{it} - (FD + Wl)_{it}$$

$$[5] \quad SLd_{it} = SLc_{it} + SLl_{it}$$

where: $SLd_t = {}_{i=1}^{n} SLc_{it} + {}_{i=1}^{n} SLl_{it}$

(i and t previously defined)

Undoubtedly some of this residual can be explained by measurement error, but there is no empirical grounds for scaling the estimates down for this reason. Thus, the estimates of delivery system seepage loss (SLd_{it}) used for purposes of statistical analysis were obtained by summing canal and lateral "residual" losses (equation 5).

A major shortcoming of this approach is that the residual estimates are not supported by (not directly comparable with) existing empirical data on seepage rates for the Government Highline canal and service laterals. On an annual (average) basis, estimates derived by the residual method appears to be 20 to 40 percent above what the best available experimental data would imply for this particular delivery system [Kruse, 1975]. In terms of the total canal-lateral system in the Valley,the estimates are probably on the low side.

However, for the purposes of analysis of historical relationships, this type of estimate is the appropriate one. The monthly data indicate a close similarity between the seasonal distribution of seepage loss and canal diversions (a relationship expected a-posteriori). Therefore, the chosen measure of seepage loss is perhaps more appropriately an "index", reflecting the intertemporal effects (both seasonal and annual) heretofore untested as an explanatory variable in subsurface return flow and quality.

On-Farm Seepage and Deep Percolation. Salt pickup from subsurface sources directly attributable to irrigation practices has not been measured for the Grand Valley as a total unit area. As discussed in section B, sound empirical data are available on a site-specific basis, but no conclusive evidence is offered to dispell the significant inconsistencies which pertain to a valley-wide characterization of on-farm pickup mechanisms.

Conceptually, the disposition of irrigation water delivered to farms is separable by component of use: on-farm conveyance seepage (SLf), crop water requirements (ETw), rootzone water storage (RZ), deep percolation (DP), and field tail water (TW). The annual on-farm water budget used to analyze these potential sources of salt pickup is represented by equation [6]. Subsurface water losses (DP and SLf) were estimated as a residual since secondary time series data only exists for (or is applicable to) those variables on the right-hand side in equation [7].

$$[6] \quad FD_t = \sum_{i=1}^{n} (SLf + ETw + RZ + DP + TW)_{it}$$

$$[7] \quad (DP + SLf)_t = FD_t - (ETw + TW + RZ)_t$$

Information on the monthly irrigation water deliveries to farms (FD_{it}) were obtained from historical records maintained by the Bureau of Reclamation [Klapwyk, 1974]. Unlike other supply canals which are operated on a "continuous flow" basis, the Government Highline Canal is under the "call system". Water is delivered at farm headgates on demand, and the delivered flows are recorded by project personnel (ditch riders) for the purpose of billing users and, in the event of water-short periods, to ration scarce supplies. Water costs to farmers served by the other canals are "fixed" at the beginning of the irrigation season and do not vary with the amounts diverted. Also, these canals carry flows in sufficient quantity to offset the need for rationing during periods of peak demands or shortages. For these reasons there might be some question as to whether the Government Highline Canal is "representative" of the other canals in terms of actual water deliveries to farms. However, owing to the low cost of water generally, and the fact that deliveries, even under periods of rationing (which are not common), are normally more than sufficient to satisfy crop requirements, it is not likely that differences between the canal systems will be very large.

The crop water requirment, ETw in equation [7] was estimated with the use of the standard Jensen equation [Jensen and Haise, 1963]. Data for the computations was obtained from the Bureau of Reclamation's project office located at Grand Junction [Wiscombe, 1975]; and [Walker,1975]. The procedure, outlined in equations 8 through 10, builds upon individual crop demands and incorporates the changing crop mix which occurs over time.

[8] $$ET_{jt} = \sum_{i=1}^{n} (ETp_i \cdot K_{ij})_t$$

[9] $$ETw_{jt} = (A \cdot ET)_{jt}$$

[10] $$ETw_t = \sum_{j=1}^{m} ETw_{jt}$$

where:

j = crop, $j = 1, 2, \ldots m$; i, t previously defined

ETp = potential evapotranspiration (inches per acre)

K = crop growth stage coefficient (% of ETp)

ET = actual evapotranspiration requirement (inches per acre)

A = crop acreage

ETw = total irrigation water requirement. (ETw ÷ 12inches = acre feet)

The aggregate estimate of total crop water demand is seasonally weighted to reflect historical growing conditions and cropping patterns which apply to the Government Highline Canal system covering the period of this analysis.

This procedure provides a fairly precise measure of the potential water requirement, but it does not purport to accurately measure the timing or amounts of water actually applied to growing crops. Other variables which play an important role in plant water requirements, for example commercial fertilizer or new crop varieties, also influence water use but could not be incorporated into the analysis. The measured variable ETw is, therefore, an index of crop water demand representing the seasonal changes in irrigation water delivered to farms in response to changes in atmospheric conditions and the growth stages of a particular mix of crops.

The aforementioned question of "representativeness" of the canal system is especially critical here, since water requirements vary measurably between types of crops. If the acreage and mix of crops served by the canal system selected for study is not representative of past trends for the Valley as a whole, then the time distribution of seasonal irrigation water deliveries obtained from the above procedure will cause a misspecification of salt pickup via deep percolation and seepage on farms equation 1 . Although scant evidence is available upon which to verify crop mix and acreage being the same for the canal and the Valley, the available data suggests that the two were reasonably similar during the period of study (1951-1972). However, this may not be true prior to the mid-forties when sizable acreages of lowlying lands (situated below the Highline Canal and contiguous to the river) were being taken out of production due to a rising water table [Bureau of Reclamation, 1956].

Estimates for tail water loss (TW) and rootzone water storage (RZ) used in the model equation 7 were adapted from the results of irrigation efficiency studies in the Valley[Walker, 1976; and Bureau of Reclamation, 1956]. Annual tail water losses were computed with the use of a fixed proportion (P_i) or percentage of monthly delivered supplies (FD_i), the proportion of runoff varying with the seasonal characteristics of the irrigated soils:

$$[11]\quad TW_t = \sum_{i=1}^{n} (P \cdot FD)_{it}$$

Essentially P reflects the rate of water applied in excess of the potential rate at which water can infiltrate the soil in a given period of time. By this method tail water loss, computed as a proportion of water delivered to the farm, is estimated for each month and varies directly with the amounts of delivered water. It was assumed that the monthly values of P are the same each year, i.e., P_i is a constant. This is perhaps an oversimplification but the limited evidence available tends to support this presumption [Walker, 1976].

Monthly depletion of water from the rooting zone of the soil profile was defined as either crop consumptive use or deep percolation. Waters entering the rootzone in excess of consumptive use during the irrigation season (April - October) were counted as percolation losses. Further, the soil moisture stored in the rootzone at the end of one season was assumed to carry over to the following season, thus natural moisture accumulation in the intervening period (November - March) was considered to be about equal to evaporative losses during the same period. On the basis of these assumptions, rootzone water storage (RZ) in equation [7] was omitted from the computations.

This summarizes the sources and nature of the empirical data used to test some of the important hypotheses discussed in section B. To conclude this section the dependent and explanatory variables which form the basis for the statistical tests are reviewed.

The Empirical Hydro-Salinity Equations

The dependent variable or quantity to be explained is defined as net salt pickup (S) in the study reach. The magnitude of salt pickup at any point in time is said to be the result of agricultural (Sa) and natural (Sn) sources. Other sources of salt loading, municipal-industrial contributions (denoted Su in equation 12), were not studied directly.

$$[12] \quad S_{it} = (Sa + Sn + Su)_{it} \qquad \text{(from [1])}$$

We distinguish between these conceptually, but in reality the separate quantities are unknowns.

A further distinction was made between surface and subsurface mechanisms. This applies to both natural and agricultural sources, but only the agricultural processes are quantifiable with existing historical data. The surface contribution from agriculture ($S\bar{a}$) is accounted for by administrative spillage in the delivery system (Wd) and tail water (TW) from irrigated fields:

[13] $S\bar{a}_{it} = (Wd + Tw)_{it}$ (from [3], [4], and [6])

Subsurface salts ($S\underline{a}$) are picked up in the seepage water of the delivery system (SLd), from water that percolates below the rootzone of irrigated crops (DP), and from head ditch seepage on the farms (SLf):

[14] $S\underline{a}_{it} = [SLf + DP]_{it} + SLd$ (from [5] and [7])

The explanatory variable used to account for natural salt loading within the reach is recorded rainfall. The amount of rain (R) is used as an index in an attempt to measure indirectly both surface runoff and ground water interchange mechanisms:

[15] $Sn_{it} = f\ (R_{it})$

These equations essentially comprise the conceptual model of the salinity-flow system for the study reach. It should be noted that the explanatory variables are all expressed in terms of water quantities while the dependent variable is expressed as quantities of salts. In this form the estimated regression coefficients will be interpreted as "rates of salt pickup" or tons of salts per acre foot of return flow waters. Since the manmade and natural portions of salt pickup are unknowns, least-squares estimation of the structural coefficients is based upon the total salt load (S in equation 12). Accordingly, estimates of Sa or Sn cannot be obtained directly from the statistical estimation procedure, but must be inferred from the explanatory power of the independent variables included in the equation.

D. RESULTS AND DISCUSSION

The results or findings are reported in three phases in accordance with the procedures followed in analyzing the data. In the first phase, annual data were used to examine the historical relationships between the various explanatory variables (developed in the previous section) and water quality for the period of study, 1951-1972. The second phase of the analysis focuses on the monthly data. An attempt was made to discern the nature of specific pickup mechanisms as they may be manifest in a monthly or seasonal context. Special attention was paid to testing of the hypothesized "seasonal" contributions of natural runoff and irrigation return flow to salt loading. The possibility of time lags in irrigation return flows was also addressed in this phase. The monthly data were aggregated into "quarters" of the year in the third phase of the study to further explore the question of seasonal effects as well as to corroborate these findings with the monthly and annual analyses.

Part I: The Annual Data

The long-term relationships between the natural and manmade variables and salt pickup are compared in a series of data plots. In figures 9 and 10 each variable is plotted with respect to time, and in figures 11 through 13, selected explanatory variables representing possible natural and irrigation contributions are plotted against net salt pickup.

The time plots yield some interesting implications. First, annual net salt pickup in the reach has apparently been declining during the period of study while irrigation diversions and water deliveries show a notable increasing trend. This observation, if true, would be contradictory to the

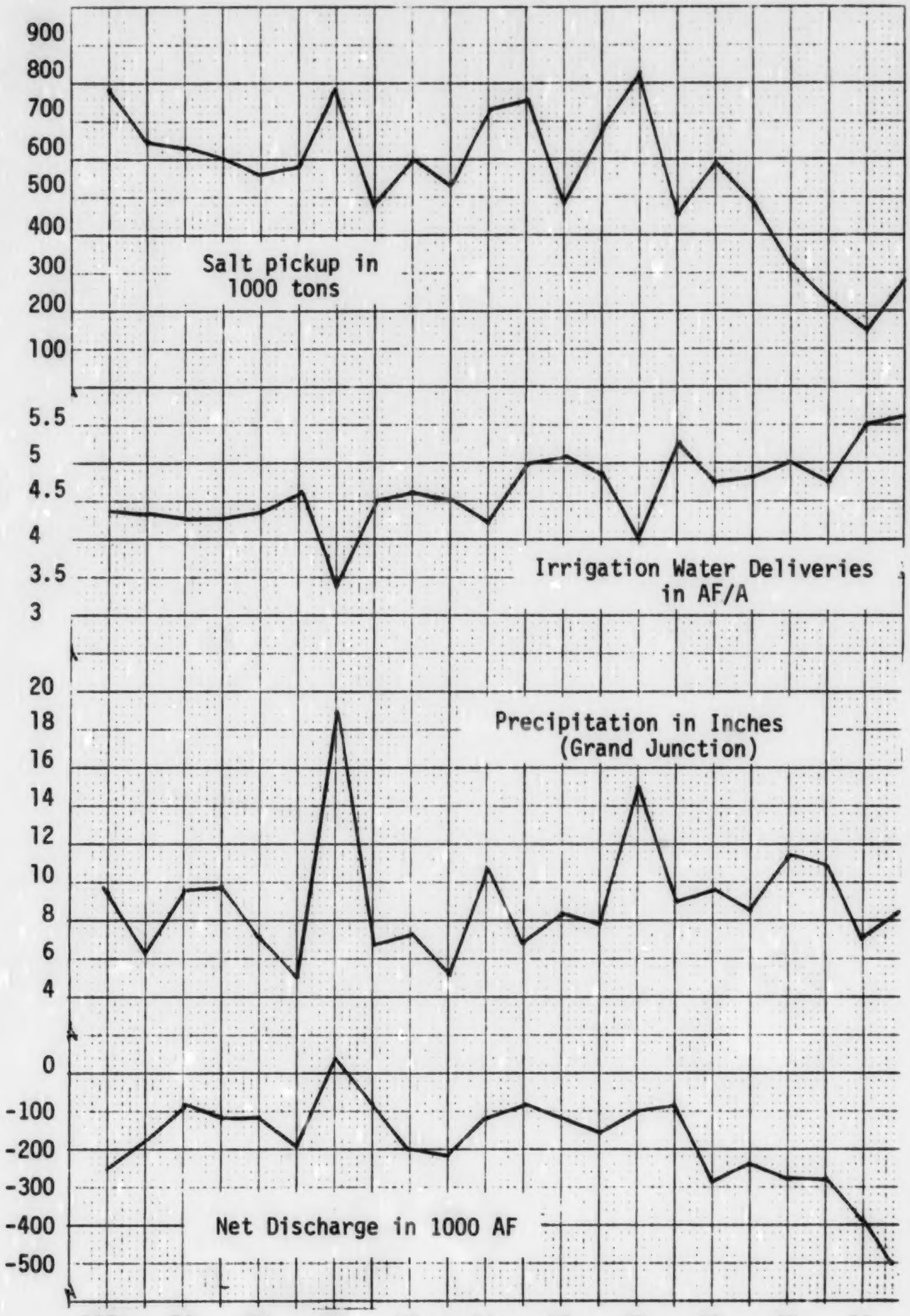


Figure 9. Annual Estimates of Salt Pickup, Irrigation Water Deliveries to Farms, Precipitation and Net Discharge for the Grand Valley Reach, 1951-1972.

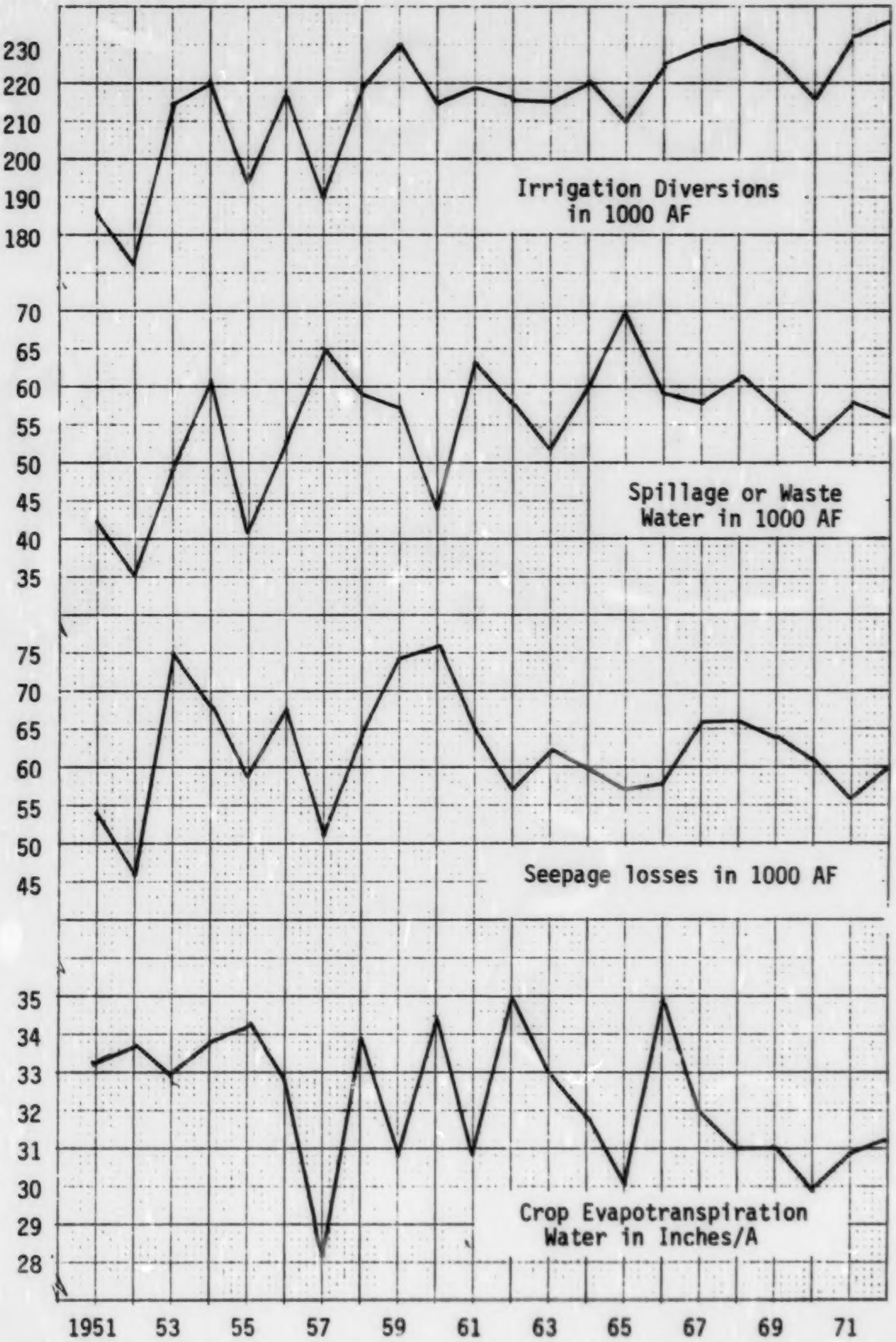


Figure 10. Annual Estimates of Irrigation Diversions, Distribution System Waste Water, Canal and Lateral Seepage Losses, and Crop Evapotranspiration for the Government Highline Canal, 1951-1972.

hypothesis that salt pickup is caused by excessive irrigation losses.* Since crop consumptive use has remained about the same during the period, irrigation return flows (as reflected in the spillage, seepage and deep percolation variables) show some increase with time. One variable which moves most closely with net salt pickup is net river discharge. This apparent relationship might be explained by increased consumptive withdrawals for municipal or industrial uses but no attempt was made to confirm or refute this conjecture.

A second general observation has to do with annual variability. It is apparent that in certain years large shifts in some of the variables are coincident. For example, the years 1957, 1961, and 1965, periods of sharp increase in salt pickup, are periods of exceptionally high annual precipitation. If the precipitation variable is an indicator of natural runoff as hypothesized, then this would tend to support the contention that natural mechanisms could be a significant source of salt loading. As expected, extremes in annual precipitation are also reflected in net discharge. The inverse relationship between extremes in precipitation and irrigation is fairly obvious, since salt pickup and irrigation are almost mirror images of each other.

Sample means, standard deviations and coefficients of variation for the regression variables are reported in table 16. The coefficient of variation (the standard deviation divided by the mean) for net discharge and deep percolation are exceptionally large due to the inclusion of positive and negative values in the range of observation. Deep percolation has the highest coefficient of variation among the irrigation variables. Intuition would suggest that seepage and canal flows should be highly related, and based upon the sample statistics, canal divisions, seepage and deliveries

TABLE 16. MEANS, STANDARD DEVIATIONS AND COEFFICIENTS OF VARIATION OF THE REGRESSION VARIABLES: ANNUAL DATA, 1951-72

Regression Variables	Unit of Measure	Statistical Parameter: Mean	Standard Deviation	Coefficient of Variation[a]
Net Salt Pickup	1000 TONS	541.14	184.36	.34
Net Discharge	1000 AF	180.67	129.91	.72
Precipitation:				
Grand Junction	inches	8.02	2.71	.34
Fruita	inches	9.05	3.03	.33
Cisco	inches	7.98	3.06	.38
Irrigation Diversions	1000 AF	216.41	24.61	.11
Seepage Losses	1000 AF	62.26	7.72	.12
Spillage	1000 AF	54.61	12.04	.22
Farm Deliveries	AF/A	4.64	.51	.11
Deep Percolation	inches/A	4.39	4.56	1.04
Crop ET	inches/A	32.05	2.10	.07

[a] Standard Deviation ÷ Mean

to farms all have a coefficient of variation of about the same magnitude.

The annual data relating each of the more important independent variables to net salt pickup are plotted in figures 11 through 13. These plots, although reflecting extreme variability in the data, suggest that some relationships do exist. However, the "fit" of the paired variables to a straight-line function is generally quite poor.

Figure 11 compares two independent variables which are indicative of natural influences (precipitation and net river discharge). Both demonstrate a positive relationship with net salt pickup, although the influence of precipitation is perhaps less clear. Increases in net discharge (denoted by smaller negative values) are hypothesized to reflect the influence of natural runoff, but in reality they also reflect irrigation diversions. Hence, this variable is a composite of many potential effects and therefore its interpretation as an explanatory variable of natural phenomena may be misleading.

River diversions and water deliveries to farms, compared in figure 12 both relate inversely to salt pickup. That is, in years of high diversions of water or deliveries to farms the salt pickup in the reach is low, and vice versa. This empirical relationship is in juxtaposition to the contention that increased irrigation efficiency will automatically lead to improved water quality, in the sense that reduced system and on-farm losses will permit less water to be diverted, thus avoiding some salt pickup. The data plots presented in figure 13, relating estimated subsurface return flow variables to salt pickup, are less clear. Seepage is positively correlated with salt pickup over the range of data, but may be more appropriately plotted in two functions: one

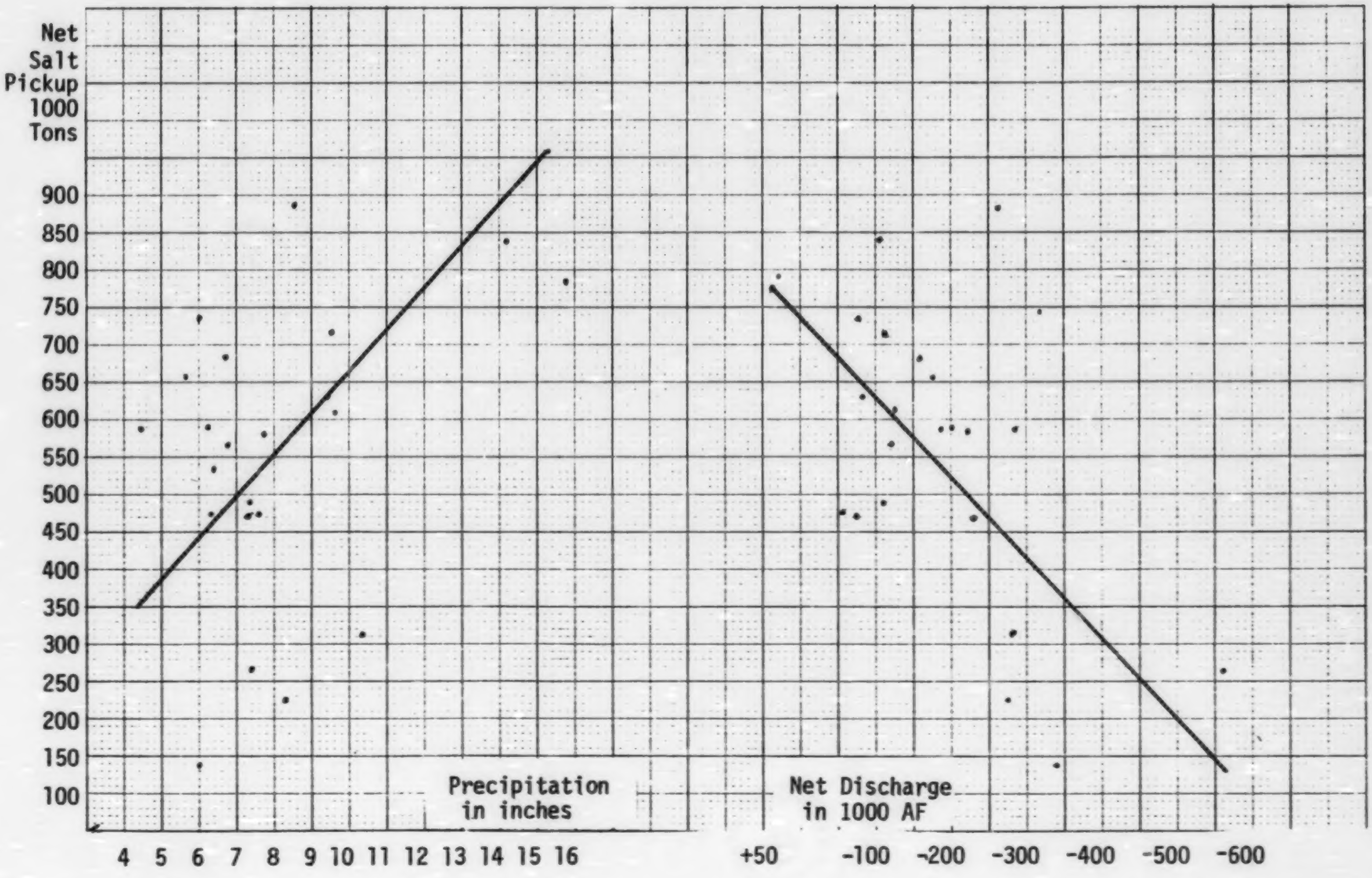


Figure 11. Data Plots of Net Salt Pickup with Precipitation and Net Discharge: Annual Data

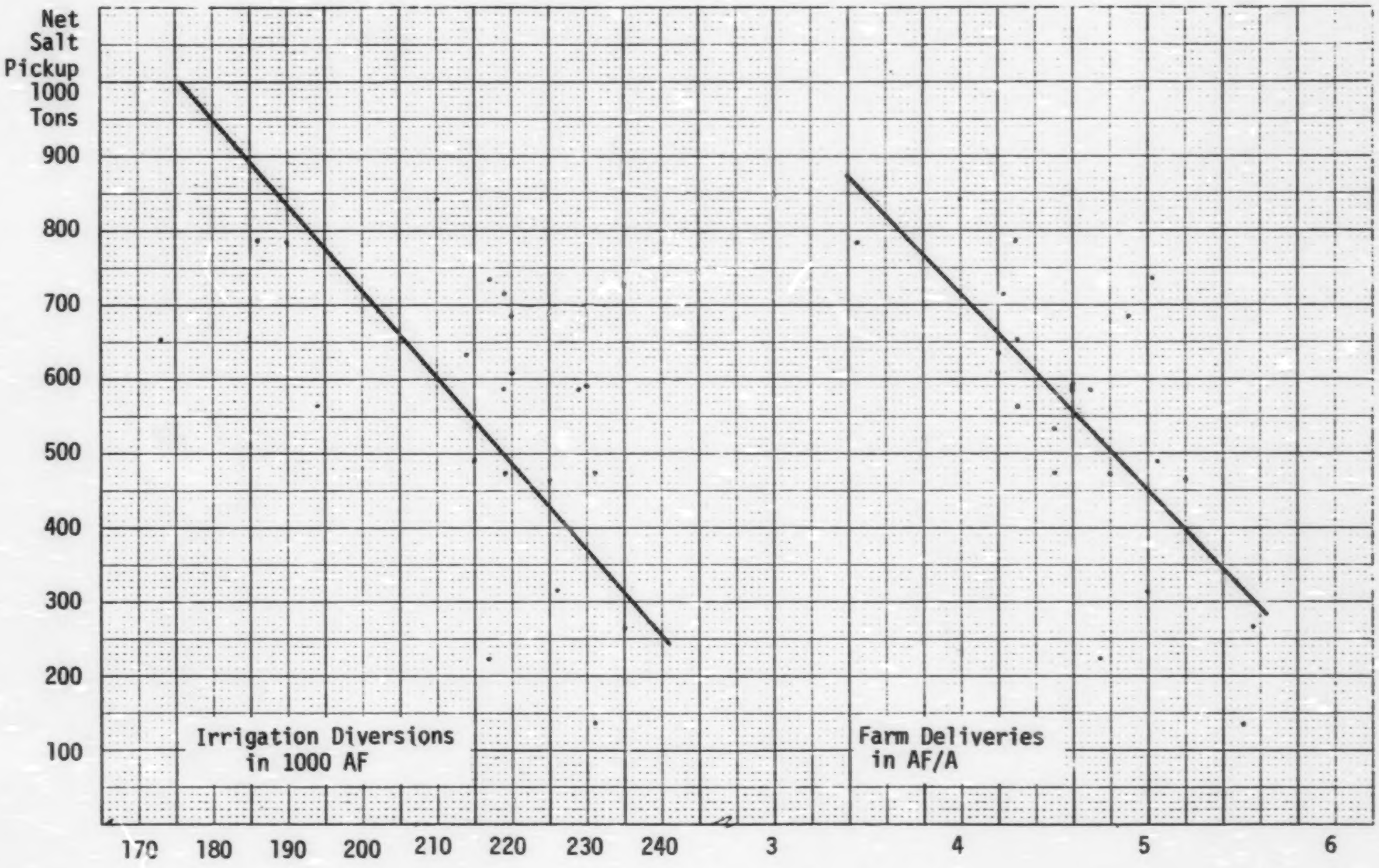


Figure 12. Data Plots of Net Salt Pickup with Irrigation Diversions and Farm Deliveries: Annual Data

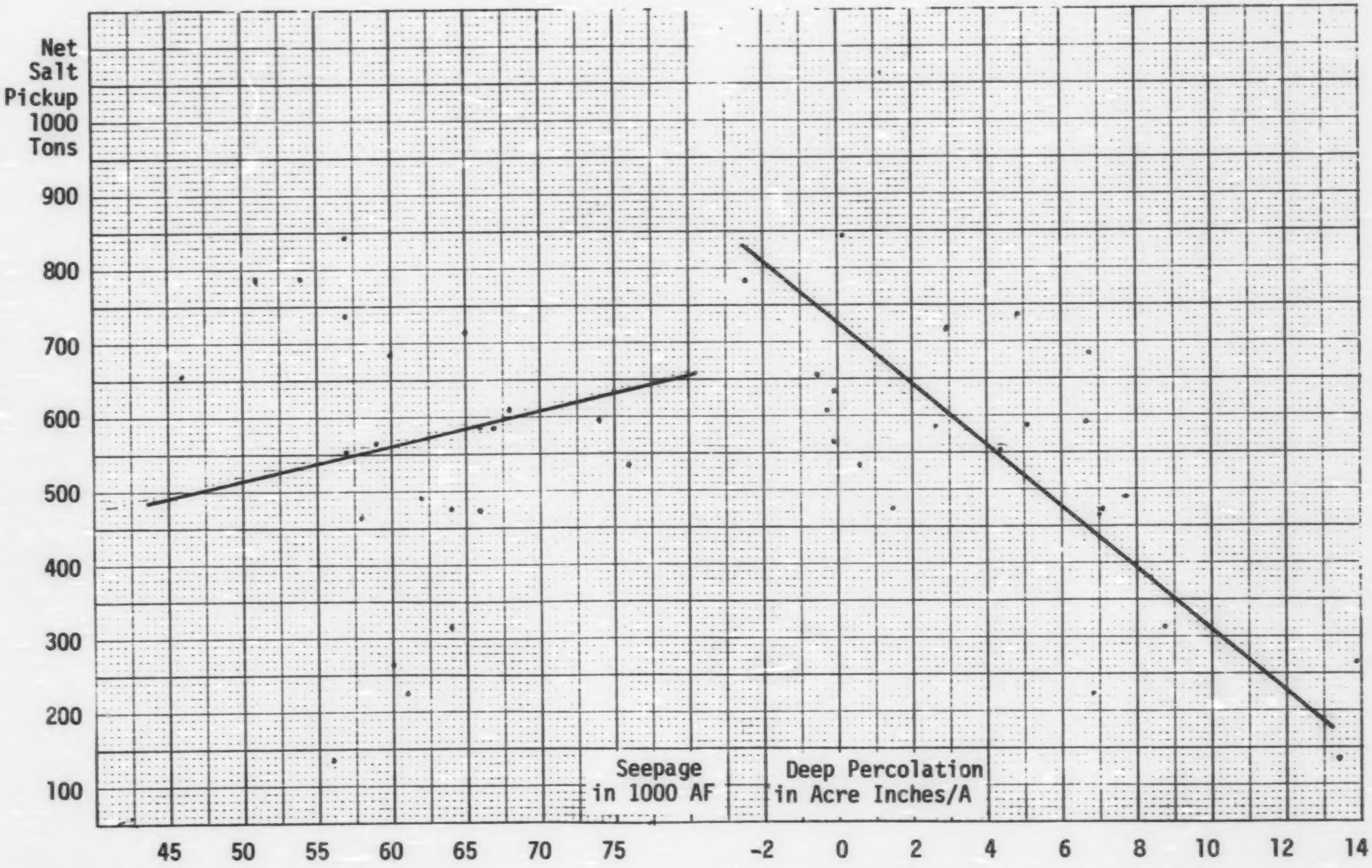


Figure 13. Data Plots of Net Salt Pickup with Canal Seepage and Deep Percolation: Annual Data

negatively sloped for salt pickup values above the mean, and one positively sloped for values of pickup below the mean. However, this kind of function is incongruous with existing theories of how the hydrosalinity system functions in the Grand Valley. The plot of on-farm losses (deep percolation and seepage) with salt pickup is similar to that found for farm deliveries, indicating an inverse relation.

The appropriate set of variables to be regressed on net salt pickup was determined by an examination of the intercorrelation between pairs of variables. If two or more explanatory variables are highly correlated, it is difficult to separate their respective effects on the dependent variable. In such cases only one variable was included in the regression equation. In multiple regression, a high interdependence between the explanatory variables will lead to biased estimates of the regression coefficients--a problem known as multicollinearity. The correlation matrix is presented in table 17.

The correlation coefficient is a measure of the degree of linear association between two variables. A negative coefficient implies an inverse relationship while a positive coefficient indicates a movement of the two variables in the same direction over the range of sampled data. An examination of the correlation coefficients reveals, for example, that the three precipitation variables are highly intercorrelated. Accordingly, only one of these, the Grand Junction data, was used in the regression analysis. Farm deliveries and deep percolation are also highly correlated, and therefore these variables could not be considered jointly in a multiple regression equation.

The specific functional form of a quantitative relationship is usually determined empirically, but consideration should always be given to the theoretical implications of doing so. The easiest functional

TABLE 17. CORRELATION MATRIX OF SELECTED VARIABLES USED IN REGRESSION: ANNUAL DATA[a]

Variable	Net River Discharge	Precipitation			Irrigation			Time
		Grand Jct.	Cisco	Fruita	FD	SLd.	(SLf+DP)	
Time	-.54	.01	.01	.09	.69	.01	.77	
Salt Load:								
Colorado R. at Cameo	.95	.26	.47	.28				-.01
Gunnison R. at Grand Jct.	.95	.56	.61	.60				.15
Dolores R. at Cisco	.90	.49	.46	.50				.09
Colorado R. at Cisco	.96	.56	.64	.56				-.12
Net Salt Pickup	.64	.36	.32	.29	-.72	.50	-.74	-.65
Net River Discharge		.33	.15	.29	-.64	-.33	-.51	
Precipitation:								
Grand Jct.			.87	.98	-.59	-.27	-.32	
Cisco				.86	-.52	-.11	-.25	
Fruita					-.53	-.16	-.23	
Farm Deliveries (FD)						-.50	.92	
Seepage (SLd)							-.58	

---

[a] Coefficients for the two-variable case only.

form to explain and estimate is a linear equation. In some cases an exponential or logarithmic function better describes the curvature of an empirical relationship. Some of the criteria that can be used to choose among the many possible forms for regression equations include simplicity, theory, predictive power, etc. However, the procedure followed in this study placed more emphasis on the estimated equations themselves: (1) the goodness-of-fit (to rely on the significance of R^2 as shown by the F statistic); (2) the significance of regression coefficients (as shown by the t statistic); and (3) the analysis of residual patterns (a test of appropriateness in equation form based on time-trend in the error term). With few exceptions, no firm justification was found, on the basis of these three considerations, to warrant the use of other-than linear equation forms.

The series of regression equations, formulated to test the explanatory power and significance of the hypothesized causal factors relating to annual net salt pickup, are reported in tables 18 through 20. In table 18 the equations which account for the natural effects are summarized.

Considered by itself annual precipitation is not a significant determinant of salt pickup (equation 18.1). The F statistic indicates that the total variation in salt pickup associated with precipitation, a measure expressed by the adjusted coefficient of determination ($\bar{R}^2$), is not significantly different from zero. $\bar{R}^2$ is the normal coefficient of determination (R^2) "adjusted" for the degrees of freedom in each regression equation.

Secondly, the t test shows that the intercept parameter ($\hat{a}$) is significantly different from zero. The regression coefficients ($\hat{b}$, $\hat{c}$, etc.) define the slope of the regression line, and are interpreted as the change in the dependent variable that is associated with a given (or specified)

TABLE 18. SUMMARY OF REGRESSION RESULTS RELATING NET SALT PICKUP TO NATURAL CAUSES: ANNUAL DATA

				Test Statistics[a]					
					t value				
Equation	Intercept	Regression Coefficient(s) (Standard Errors)	R^2	F Ratio	$\hat{a}$	$\hat{b}$	$\hat{c}$	$\hat{d}$	d.w.
1	339.4 (122.4)	+ 25.15 R (14.49)	.14	3.01	2.77	1.74			1.34
2	1478.9 (311.2)	+ 26.27 R - 18.52 T (11.04) (4.83)	.53	9.96	4.75	2.38	3.83		.99
3	724.8 (50.1)	+ 1.017 F (.23)	.51	20.02	14.47	4.48			2.07
4	1092.0 (349.2)	+ .809 F - 6.46 T (.40) (6.1)	.52	4.59	3.13	2.01	1.06		2.07
5	633.6 (119.5)	+ .947 F + 9.81 R (.24) (11.65)	.53	7.48	5.30	3.90	.84		1.41
6	607.7 (143.7)	+ .65 F + 12.72 R + .038 (FR) (.89) (14.62) (.11)	.53	6.51	4.23	.73	.87	.35	1.87

[a] Critical values at the 5 percent level of significance:

$F(n_1, n_2)$: (1,20) = 4.35; (2,19) = 3.52; (3,18) = 3.16; (4,17) = 2.96

t (df): (20) 2.09; (19) 2.09; (18) 2.10; (17) 2.11

d.w. (n, k'): (22,1) = 1.12>d.w.>1.31; (22,2) = 1.04>d.w.>1.42; (22,3) = .95>d.w.>1.54

change in the independent variable(s). The intercept, $\hat{a}$, is the constant term in the equation, or the point on the vertical axis (which describes the range in observation values of the dependent variable) through which the regression line passes. Lines of regression between net salt pickup and the separate independent variables are shown with the data plots described earlier (figures 11 through 13). But as other statistical tests will demonstrate, one-on-one relationships can be misleading in terms of identifying meaningful empirical relationships.

Third, the Durbin-Watson statistic (d.w.), which is a measure of "serial" correlation (i.e., the degree of correlation between the dependent variable and the error term), indicates the regression equation might be misspecified (i.e., an additional variable or variables should be included in the equation). Thus, when time (T) is included in the equation (shown in 18.2), the explanatory power of the equation is substantially enhanced. Improvements are also noted in the level of significance of the regression coefficients ($\hat{a}$, $\hat{b}$, and $\hat{c}$ are now significant), and by the absence of some serial correlation.

In equation 18.3 net river discharge is shown to be a significant factor in explaining net salt pickup. Since time and net discharge are intercorrelated (table 17), the addition of the time variable does not improve the equation (18.4). In equation 18.5 net discharge and precipitation are considered together. In this case the addition of precipitation reduces the level of significance of the other coefficients and introduces some serial correlation into the equation. Use of the interactions term FR, computed by multiplying variable F by R, is one method of reducing regression bias caused by serial correlation. However, it is shown in equation 18.6 that, although including the interactions term increases the d.w. statistic, the significance of the regression coefficients is also reduced, indicating that the estimated parameters in equation 18.5 may have an upward bias. But, the fact that the interaction term is not significant would suggest that the degree of regression bias is not large enough to warrant including the term in the equation.

The evaluative approach described above was used to carefully examine each regression equation reported in subsequent tables. In the remainder of this chapter only the more general observations and findings of the analyses are discussed. Interpretations as to the meaning of specific regression coefficients, for example, the change in salt pickup attributed to a specified change in seepage water, will be taken up in the summary portion of this section.

The results of the analysis of manmade effects are summarized in table 19. Perhaps the most important observation to be made here is that all but the seepage variable (SLd) have negative signs. The time variable did not materially improve any of these regression equations. A new variable, total irrigation return flows, was computed by subtracting crop evapotranspiration from river diversions. Since surface return flows (Wd and TW) were not tested directly as were the other variables, this variable (RD - ET) is used to represent the combined effect of both surface and subsurface sources. The influence of total irrigation return flow on net salt pickup was not significant. In general, these results establish a statistically significant but inverse relationship between the subsurface components and the net pickup of salts.

A second approach is to consider the joint influence of natural and manmade variables in the same equation. In this form the empirical equation is more realistic in terms of the total water-salt relations for the study

TABLE 19. SUMMARY OF REGRESSION RESULTS RELATING NET SALT PICKUP TO SELECTED MEASURES OF IRRIGATION VARIABLES: ANNUAL DATA

				Test Statistics[a]					
					t value				
Equation	Intercept	Regression Coefficient(s) (Standard Errors)	$\bar{R}^2$	F Ratio	$\hat{a}$	$\hat{b}$	$\hat{c}$	$\hat{d}$	d.w.
1	1754.9 (271.1)	- 261.80 FD (58.14)	.50	21.88	6.47	4.50			.88
2	1628.7 (372.5)	- 162.30 FD - 5.16 T (86.80) (6.64)	.28	4.25	4.37	1.87	.78		.93
3	282.4 (108.8)	+ 4.54 SLd (1.80)	.21	6.35	2.60	2.52			1.20
4	1294.4 (430.4)	+ 2.47 SLd - 14.42 T (1.82) (5.97)	.37	6.89	3.01	1.35	2.41		1.53
5	673.3 (38.6)	- 30.13 (SLf + DP) (6.19)	.54	23.73	17.42	4.87			1.35
6	831.9 (184.4)	- 13.02 (SLf + DP) - 22.04 T (8.99) (16.20)	.36	3.75	4.51	1.45	1.36		1.19
7	611.7 (125.6)	+ .90 SLd - 27.82 (SLf + DP) (1.74) (7.77)	.51	7.85	4.87	.52	3.58		1.24
8	889.0 (255.9)	- 3.75 SLd - 50.51 (SLf + DP) (4.13) (19.88) + .44 [SLd (SLf + DP] (.36)	.53	6.98	3.47	.91	2.54	1.24	1.49
9	1211.4 (348.4)	- 87.03 (RD - ET) (44.32)	.13	3.86	3.53	1.96			1.07
10	1644.1 (350.9)	+ 21.73 (RD - ET) - 20.49 T (58.85) (8.25)	.31	3.53	4.69	.37		2.48	1.30

a/ Refer to table 18, footnote [a], for critical values.

reach, and by including both types of effects, their separate importance is more clearly ascertained. These results, summarized in table 20, are generally inclusive. Because of the interaction between rainfall and irrigation, the rainfall variable is not significant in any of the equations pairing rainfall with the return flow variables. The flow variable was not used here because of problems with multicollinearity.

In summary, the analysis of annual data demonstrates the difficulty of isolating causal factors which explain annual variations in water quality. The relationship between precipitation (or net river flow) and irrigation activity in the study reach does not allow a statistically significant separation of their individual effects. However, in the two variable cases the importance of natural or manmade sources is identifiable and significant, but in this form the regression equations are not consistent with the conceptual hydrosalinity model. Regression parameters for natural sources exhibit the appropriate sign, but variables associating salinity to irrigation have the wrong sign to confirm a positive impact from this source.

An important objective of the study was to evaluate the effects of time on changes in salt pickup. In some cases including a time variable enhanced the explanatory power of the regression equation. During the years covered by the analysis, annual salt pickup in the study reach declined significantly with time. This means that the combined hydrosalinity processes during the period functioned in such a way that they contributed to a lessening of net salt pickup. And since it was shown that irrigation return flows tended to increase during the same period, this finding is at least a cause to question further the deleterious impact irrigation is believed to have on the salinity problem in the Grand Valley area.

TABLE 20. SUMMARY OF REGRESSION RESULTS COMBINING THE NATURAL AND MANMADE CAUSES: ANNUAL DATA

				Test Statistics[a]					
					t value				
Equation	Intercept	Regression Coefficient(s) (Standard Errors)	$\bar{R}^2$	F Ratio	$\hat{a}$	$\hat{b}$	$\hat{c}$	$\hat{d}$	d.w.
1	977.1 (357.7)	+ 22.67 R - 80.21 (RD - ET) (13.67) (42.61)	.20	3.48	2.73	1.66	1.88		.70
2	1879.1 (416.4)	- 5.49 R - 279.09 FD (13.72) (73.55)	.47	9.77	4.51	.40	3.80		.90
3	593.9 (107.8)	+ 8.83 R - 28.17 (SLf + DP) (11.26) (6.70)	.52	11.68	5.51	.748	4.21		1.33
4	204.2 (376.5)	+ 26.30 R + 2.024 SLf (15.13) (5.32)	.05	1.51	.54	1.74	.38		.62

---

[a] Refer to table 18 footnote [a], for critical values.

Part II: The Monthly Data

The monthly data are perhaps more appropriate to the study of salt pickup processes. Rainfall and irrigation events are more "seasonal" in nature, and thus the influence of these factors will not always show up distinctly in the annual data. Plots of the sample means, which pertain to the 1951-1972 period, are depicted in figures 14 and 15. In figure 14 the monthly distribution of mean net salt pickup, farm deliveries and precipitation (recorded at Grand Junction) are compared. The implications suggested by these data are several. First, the monthly distribution of salt pickup appears to follow a definite pattern possibly reflecting both the influence of irrigation and precipitation. In June the function registers a sudden increase and later in the year, about October, the function peaks out. The sharp increase about mid-year is fairly consistent from year to year, and thus represents a unique event to attempt to explain.

Second, it is noted that the monthly distribution of farm deliveries follows nearly the same general form as salt pickup. The initial jump in water use occurs one month prior to the sudden increase in net pickup, and might be attributed to the general practice of preirrigation in the Valley. The month of highest irrigation diversion (and use) typically occurs in July, and this could coincide with peak salt pickup later in the year if a sufficient time lag is allowed for return flows to reach the river.

Lastly, the precipitation-runoff ratios discussed in table 15 indicate that the period of most significant runoff can be expected to occur late in the summer (August through October) when monthly precipitation is the largest and of greatest intensity. The peak salt load does appear to coincide with peak precipitation, especially in the month of October. A

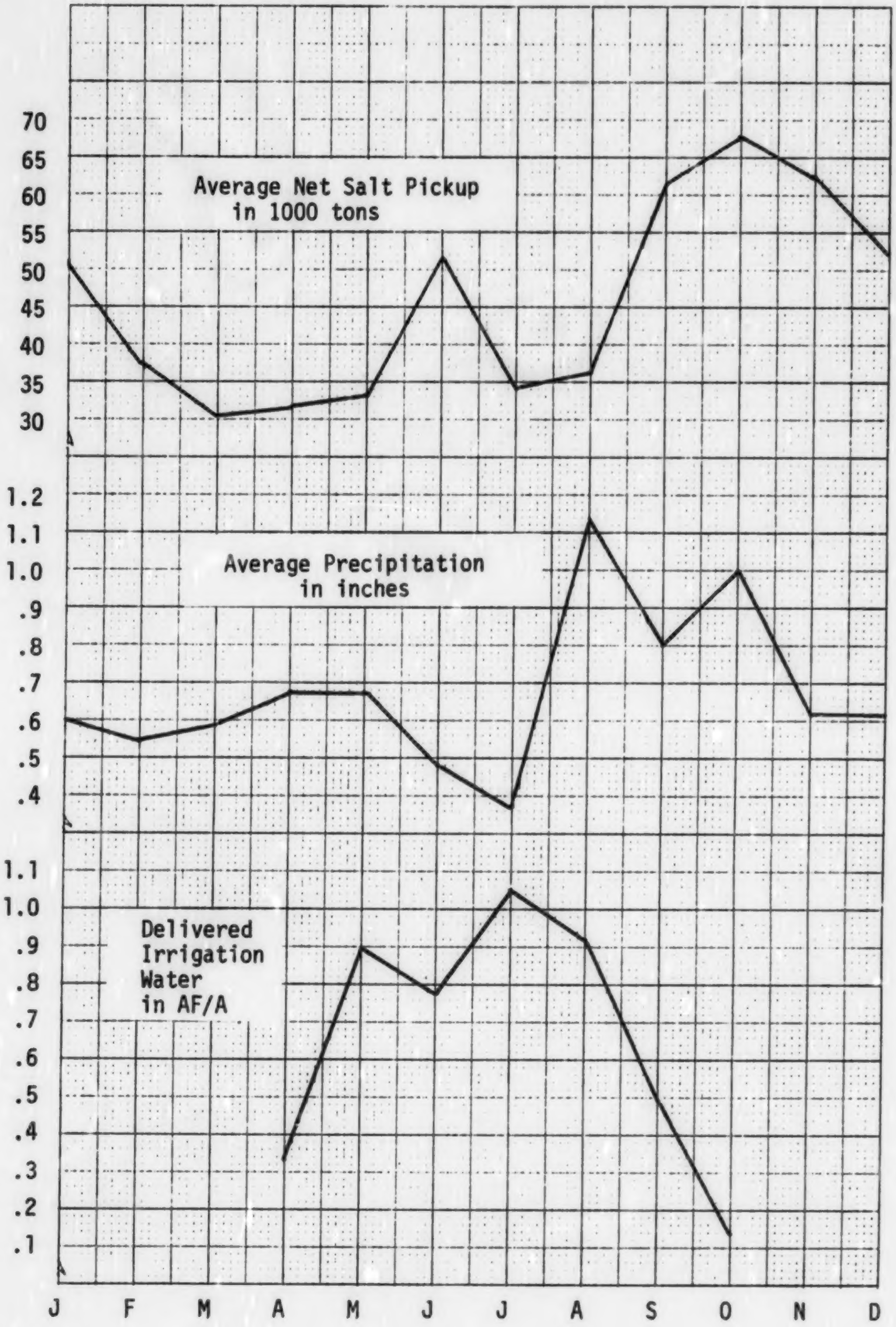


Figure 14. Monthly Mean Estimates of Net Salt Pickup, Precipitation and Delivered Irrigation Water for the Government Highline Canal, 1951-1972.

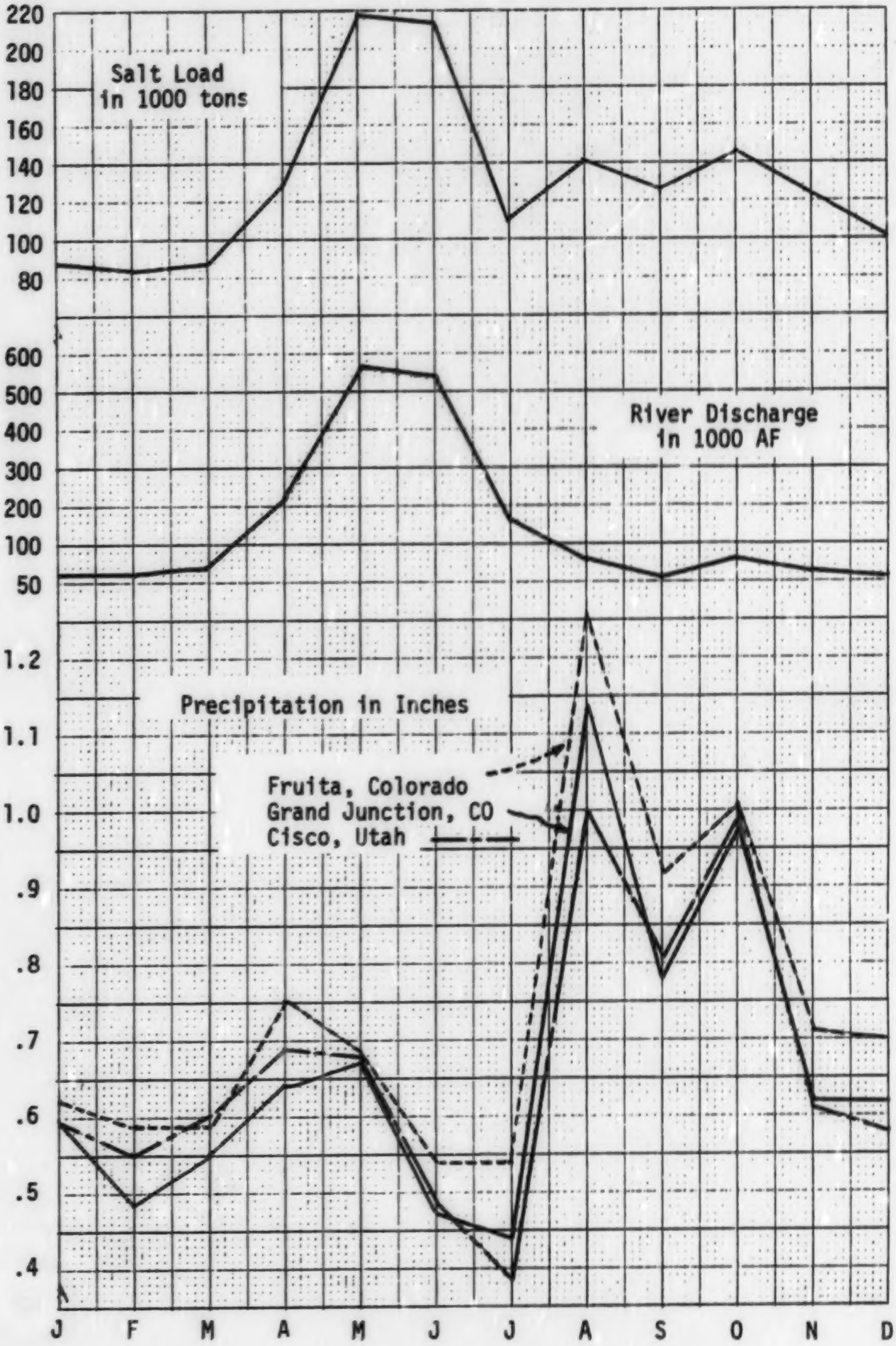


Figure 15. Monthly Mean Discharge and Salt Load of the Gunnison River, and Precipitation at Three Locations in the Grand Valley Reach, 1951-1972.

better indication of the possible importance of runoff sources can be seen in figure 15. Here, the monthly mean distribution of salt loads carried by the Gunnison River, calculated for the same period of analysis, is described along with its seasonal mean flow and area precipitation data. The Gunnison River Basin is quite similar to the study reach in that much of the nonirrigated drainage area is composed of soils derived residually from Mancos shale. The relationship between salt load and flow is apparently highly related. Also, the variations in salt load and precipitation in the months of July, August, September and October are indicative of the natural runoff effect. The noticeable increase in flow in October, if it can be attributed to overland runoff, will further support this hypothesis.

Other components of irrigation return flow are plotted in figure 16. These data show the relationship between the monthly means for farm deliveries, crop consumptive use (ET water), field tail water, deep percolation (including on-farm seepage losses), canal and lateral seepage, and administrative spills. It is important to observe that the deep percolation variable is largest in May, but for the balance of the irrigation season its magnitude is quite small. Nonetheless, deep percolation has been considered to be a significant contributor of salinity in the Grand Valley; and for this reason, year-to-year variations in magnitude are perhaps more significant than its "mean" value.

The extent of variation observed in the monthly regression variables is summarized in table 21. In contrast to the annual data, monthly variations are more extreme as indicated by many coefficients of variation exceeding a value of 1. Months with high coefficients are apparently "transition" periods, most notably the beginning and ending of the

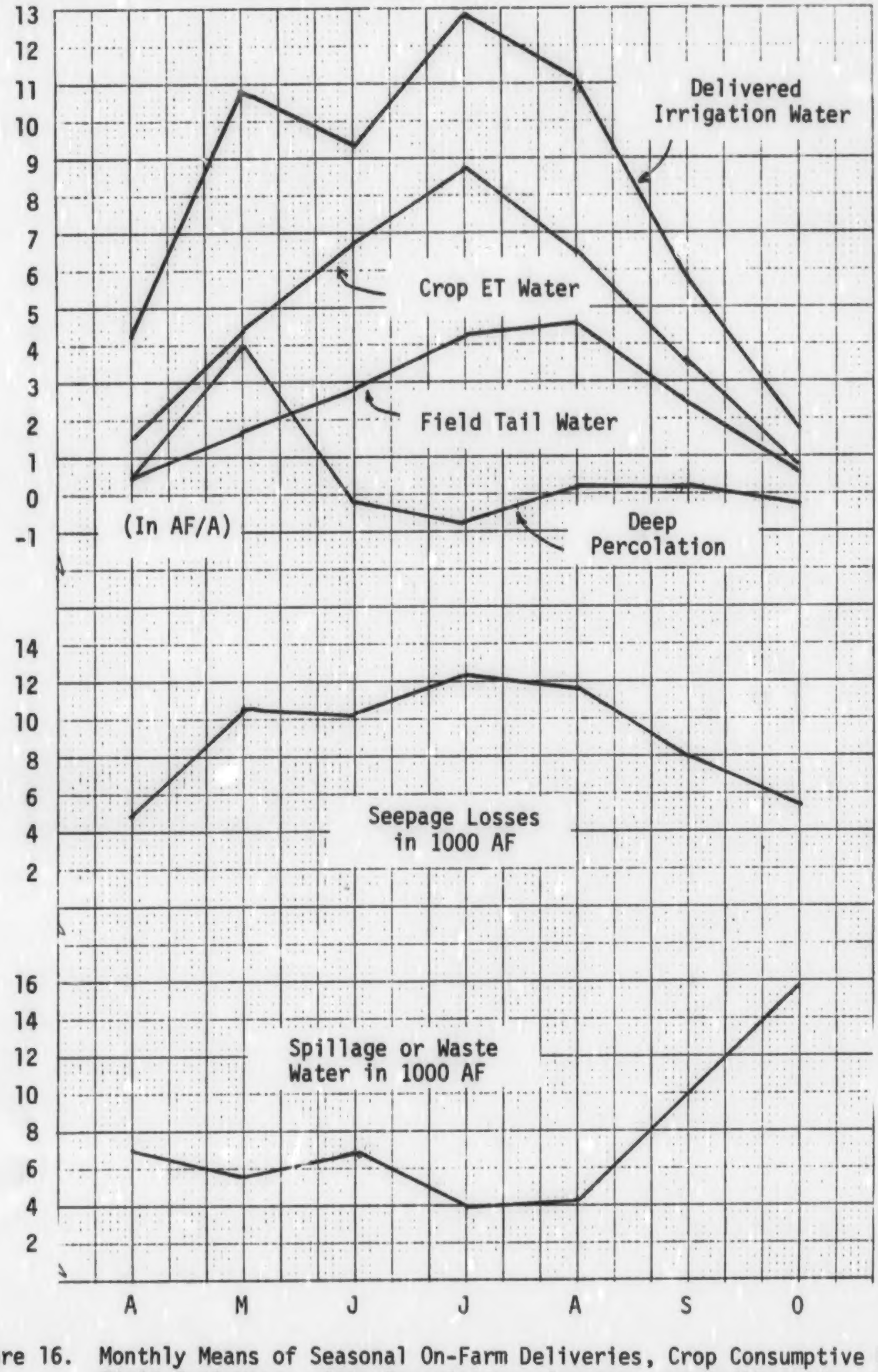


Figure 16. Monthly Means of Seasonal On-Farm Deliveries, Crop Consumptive Use, Field Tail Water, Deep Percolation, Seepage, and Spillage for the Government Highline Canal, 1951-1972.

TABLE 21. COEFFICIENTS OF VARIATION FOR SELECTED REGRESSION VARIABLES: MONTHLY DATA

Month	Coefficients of Variation					
	Net Salt Pickup	Net River Discharge	Precipitation (Grand Jct.)	Irrigation Variables		
				FD	SLd	(SLf + DP)
January	.62	1.50	.84			
February	.59	1.23	.74			
March	1.14	1.67	.83			
April	.72	.79	.72	.63	.43	16.32
May	1.37	.55	.74	.14	.12	.30
June	.74	.76	1.06	.14	.12	15.40
July	.84	.37	.81	.09	.11	.78
August	.92	.52	.79	.17	.12	2.75
September	.57	.96	.97	.23	.18	1.85
October	.73	4.87	.82	.54	.30	2.09
November	.44	1.31	.59			
December	.65	4.32	.74			

irrigation season, the summer storm period, and spring snowmelt.

Table 22 reports the correlation coefficients of the monthly variables. Correlations between the net discharge variable and salt pickup are generally higher during the first and last few months of the year, the period of normal low flow. However, the correlations also show higher positive coefficients during two of the summer storm months, August and September. For the rainfall data, the largest coefficients also occur during this period which is consistent with the plotted data in figure 14. Farm deliveries and deep percolation are inversely correlated with salt pickup in all but the early part of the irrigation season. On the other hand, the seepage variable is positively correlated in all but the last two months. The time variable indicates a negative relationship generally during nonirrigation months but a positive (although weak) relation during the months of April, May, July and August. The intercorrelation between the independent variables is not shown in table 22, but was taken account of in selecting variables for the regression runs.

A second set of correlation coefficients is reported in table 23. These coefficients provide some insight into the possibility of lagged irrigation return flows. If a lag does exist, then the correlation of irrigation variables directly with salt pickup (table 22) would not show this. A careful examination of these data, however, does not strongly support the existence of return flow lags. Correlation coefficients relating to seepage show some increase when lagged one, two and even three months, but in general the difference does not appear large enough to materially affect the significance of the regression coefficients. Farm

TABLE 22. CORRELATION COEFFICIENTS BETWEEN THE REGRESSION VARIABLES AND NET SALT PICKUP: MONTHLY DATA[a/]

Net Salt Pickup	Net River Discharge	Precipitation			Irrigation			Time
		Grand Jct.	Fruita	Cisco	FD	SLd	(SLf + DP)	
January	.79	.29	.23	.23				-.79
February	.52	.16	.17	.18				-.38
March	.50	.22	.17	.13				-.44
April	.17	.43	.43	.31	-.30	.12	-.29	.17
May	.19	-.03	-.12	.13	.10	.50	.02	.42
June	.46	-.18	-.33	-.10	.11	.37	-.12	-.03
July	.01	.42	.51	.53	-.36	.30	-.30	.08
August	.64	.48	.41	.54	-.49	.48	-.36	.10
September	.58	.59	.66	.57	-.65	-.08	-.55	-.01
October	.31	.47	.44	.63	-.29	-.30	-.24	-.24
November	.78	.18	.25	.27				-.42
December	.79	.11	.04	-.01				-.46
Annual	.64	.36	.29	.32	-.72	.50	-.74	-.65

[a/] Coefficients for the two-variable case only.

TABLE 23. CORRELATION COEFFICIENTS RELATING THE INFLUENCE OF TIME-LAGS IN SUBSURFACE IRRIGATION RETURN FLOWS ON SALT PICKUP: MONTHLY DATA[a]

Net Salt Pickup	Lagged Subsurface Irrigation Return Flows (in months)									
	Canal and Lateral Seepage (SLd)					Deep Percolation (SLf + DP)				
	No lag	1	2	3	4	No lag	1	2	3	4
April	.12					-.29				
May	.50	.56				.02	-.17			
June	.37	.40	.33			-.12	.20	-.22		
July	.30	.32	.34	.13		-.30	-.43	-.30	-.36	
August	.48	.52	.47	.50	.41	-.36	-.21	-.23	.06	-.20
September	-.08	.20	.14	.18	.17	-.55	.11	-.20	.17	.07
October	-.30	-.31	-.25	-.30	-.19	-.24	-.17	-.14	.04	.18
November		.23	.18	.23	.21		.19	-.16	-.55	-.36
December			.20	.18	.17			.18	-.15	-.62
January				.09	.04				-.14	-.28
February					-.11					.04

[a] Coefficients for the two-variable case only.

deliveries are not reported here since the results are similar to those for deep percolation (due to a high intercorrelation between these two variables).

It is not necessary to report the complete regression results as the estimated equations are not in themselves particularly meaningful. Rather, the β coefficient and level of significance of each estimated parameter are reported in table 24 as a convenient way to summarize the rather large volume of results. The conclusions to be drawn from the statistical tests have important implications in terms of the hypothesized "seasonal" effects. First, the only months in which precipitation is significant as an explanatory variable are the high rainfall months of August and October. July and September are significant at the 6 and 9 percent levels, respectively. These results are offered as a confirmation of the runoff hypothesis. Secondly, the influence of irrigation on net salt pickup is less significant. The only variable that is both statistically significant and has the appropriate sign is deep percolation, and this occurs only in May, the month of excessive irrigation losses attributed to preirrigation practices in the Valley.

Estimates of the magnitude of salts contributed by precipitation or deep percolation are not ascertainable from the results given in this form. Relative contributions of salts by source will be discussed in section E. A series of regression runs testing the lagged return flow variables (i.e., time lags of one to four months after each month in the irrigation season) did not yield any consistent results. For this reason, a quarterly analysis of the data was undertaken as a means to further explore this question.

TABLE 24. SUMMARY OF THE MONTHLY REGRESSION ANALYSES: REGRESSION COEFFICIENTS AND TESTS OF SIGNIFICANCE[a]

	Regression Coefficients (and Significance[b])				
			Irrigation Variables		
Net Salt Pickup	Net Discharge	Precipitation (Grand Jct.)	FD	SLd	(SLf + DP)
January	1.92 (.01)	2.09 (.83)			
February	.92 (.01)	.25 (.98)*			
March	1.82 (.02)	6.45 (.66)			
April	.18 (.46)	24.36 (.58)	-30.41 (.18)	-1.08 (.69)	-2.78 (.80)
May	.28 (.39)	-2.37 (.91)*	38.19* (.64)	5.93 (.23)*	.70 (.01)*
June	.60 (.03)	-8.87 (.55)	40.24 (.61)	3.16 (.63)	-5.96 (.59)
July	.02 (.97)*	40.81 (.06)	-113.02 (.10)	-6.60 (.05)	-9.03 (.18)
August	1.11 (.01)	18.91 (.05)	-103.10 (.02)	-2.01 (.64)*	-11.29 (.11)*
September	1.11 (.01)	17.20 (.09)	-199.92 (.01)	-8.13 (.14)*	-29.49 (.01)
October	.74 (.16)*	33.09 (.01)	-184.60 (.19)	-6.25 (.36)	-21.98 (.30)
November	1.60 (.01)	.14 (.99)*			
December	1.48 (.01)	12.27 (.26)*			

---

[a] Coefficient for the two-variable case only.

[b] Calculated t values are used, where .02 denotes a regression coefficient is significant at the 2 percent level. The notation [*] indicates significant serial correlation at the 5 percent level.

Part III: The Quarterly Analysis

Due to the extreme variability of the monthly data, it was conjectured that monthly variables might not be appropriate for testing salt loading effects caused by irrigation. If the incidence of irrigation in the spring of each year is highly influenced by early season weather conditions, perhaps the quantity of return flow water would be more consistent from year to year if measured over a period of months. Thus, the aggregated data were thought to be a better form in which to test the plausibility of lagged effects.

The monthly data were aggregated into four three-month quarters, roughly corresponding to the four seasons--spring, summer, fall and winter. This is not entirely consistent with a normal irrigation cycle of seven months in the Grand Valley, but the spring and summer quarters--April-June, and July-September, respectively--account for a major proportion of annual irrigation water use (refer to figure 16). The spring quarter encompasses preirrigation and early season irrigation while the summer quarter essentially represents the period of peak water use. What little irrigation that typically occurs in October was not considered important enough not to omit it from the analysis. Alternative formulations of the aggregated data may in fact be better than "seasonal" quarters, but time and resource constraints did not permit a more detailed study of these considerations.

The means, standard derivations and coefficients of variation for the quarterly variables, summarized in table 25, provide some new insight into the nature of the problem. Net salt pickup is shown to be higher in the last two quarters of the year and less variable in comparison with the first two quarters. Net discharge is lowest in the spring quarter. This

TABLE 25. MEANS, STANDARD DEVIATIONS AND COEFFICIENTS OF VARIATION FOR THE QUARTERLY DATA

Variable	Mean	Standard Deviation	Coefficient of Variation
Net Salt Pickup:			
January-March	118.48	72.14	.61
April-June	114.19	83.05	.73
July-September	126.52	68.09	.54
October-December	180.90	95.17	.53
Net Discharge:			
January-March	25.43	30.99	1.22
April-June	-116.24	52.33	.45
July-September	- 99.86	43.32	.43
October-December	9.90	48.08	4.86
Precipitation (Grand Junction):			
January-March	1.72	.80	.47
April-June	1.87	1.01	.54
July-September	2.25	1.02	.45
October-December	2.19	1.10	.50
Farm Deliveries:			
April-June	2.04	.33	.16
July-September	2.44	.26	.12
Seepage:			
April-June	25.40	3.33	.13
July-September	31.57	3.51	.11
Deep Percolation (SLf + DP):			
April-June	4.62	3.32	.72
July-September	.03	1.84	61.33

seems contrary to the fact that crop consumptive use is highest in the third quarter, and thus should be reflected by net discharge being the lowest at this time. However, this is consistent with the hypothesis of a time lag in irrigation return flow (about three months according to Hyatt, [1970]), and it possibly accounts for the increased salt pickup which seems to occur in the last two quarters of the year. This inference is bolstered by relatively high seepage and deep percolation in the spring in contrast to farm deliveries which follow closely the pattern of consumptive use (figure 16). As anticipated, the quarterly precipitation data now show substantially less variation.

The results of the regression analyses are summarized in table 26. In part A, the correlation coefficients are given; in part B, the estimated b parameters and significance levels are shown; and in part C, the regression runs of selected lagged variables are presented. Consistent with the annual data, the time variable is negatively correlated with salt pickup, and among the three irrigation variables only seepage is positively correlated with salts. The quarterly data do improve the significance level of the regression coefficient for seepage; in this case both the spring and summer parameters have appropriate signs and are significant (the summer quarter parameter at 6 percent). Rainfall is not a particularly meaningful variable in any quarter, whereas the flow variable is most significant during the fall and winter, typically the low flow period of the year.

In terms of a three-month lag, the only period in which significant irrigation return flows are indicated to have a positive effect on salt pickup occurs in the spring. Seepage loss in April through June has a significant positive impact on net salt loading in the following quarter

TABLE 26. SUMMARY OF THE QUARTERLY CORRELATION-REGRESSION RESULTS AND TESTS OF SIGNIFICANCE[a]

Net Salt Pickup	Net Discharge	Precipitation (Grand Jct.)	Irrigation-Variables			Time
			FD	SLd	(SLf + DP)	
A. Correlation Coefficients						
January-March	.67	.25				-.76
April-June	.37	.13	-.58	.35	-.65	-.14
July-September	.42	.34	-.12	.48	-.13	-.17
October-December	.67	.19				-.36
B. Regression Coefficients (and level of significance)						
January-March	1.08 (.01)	22.23 (.28)*				
April-June	.59 (.10)*	10.69 (.57)*	-51.56 (.37)*	5.16 (.02)	-6.12 (.28)	
July-September	.67 (.06)*	21.98 (.14)	-87.13 (.14)	2.80 (.06)	-12.39 (.14)	
October-December	1.34 (.01)	16.62 (.40)*				
C. Regression Coefficients (and significance level) for a three-month lag in Return Flows						
April-June		4.61 (.55)*				
July-September		-5.14 (.66)	-7.27 (.46)	3.70 (.05)	.55 (.92)*	
October-December		16.10 (.36)	-166.56 (.04)	-2.95 (.19)	-1.84 (.42)*	
January-March		-21.32 (.14)				

---

[a] Refer to footnotes [a] and [b], table 24.

(July-September). In the same period deep percolation has the appropriate sign but is not significant. The relatively high salt pickup which occurs in the last quarter of the year is not significantly related to any single variable in the preceding period (except farm deliveries, in which case the sign is negative).

In summary the quarterly analyses indicate some improvement over the monthly data in that the effects of the irrigation variables appear to be more accurately measured. On the basis of the results, the seepage component of irrigation return flow is the only variable which is significantly related to salt pickup. The regression coefficient relating summer quarter salts to spring quarter seepage shows improved statistical significance over the nonlagged regression, and therefore is an indication (not a confirmation) of the presence of a lag in subsurface return flows. Whether the appropriate lag is two, three or four months is a question that might be answered by further study of the aggregation scheme.

E. SUMMARY AND IMPLICATIONS

This chapter has reported an investigation of the sources of net increase in dissolved solids which occurs each year in the Grand Valley reach of the Colorado River. Earlier studies of this reach concentrated on the identification of salt pickup mechanisms, emphasizing agricultural causes which were believed to be responsible for nearly all the addition to the rivers' salt load as it passed through the irrigated area. Consequently, natural pickup mechanisms, which are known to contribute significantly to the salt burden of streams in other regions of the Basin, have not received the careful attention of researchers in the Grand Valley.

The purpose of this inquiry was to focus on questions relating to the incidence of salt pickup which have not been adequately considered (or answered) in the previous investigations, but questions, nonetheless, that have a definite bearing on the economics of proposed control programs. Two such questions of major importance are: (1) What is the long term significance of salt pickup in the study reach (its magnitude, trends, etc.,) in the absence of controls?, and (2) What are the likely consequences, in terms of salt load reductions, that can be credited to the various strategies, both direct and indirect, for controlling salinity? The economic implications of adopting alternative controls will not be meaningful or relevant to public policy unless these and related questions are answered with some degree of confidence.

The analysis was formulated with the principal objective in mind of testing hypotheses regarding (1) the nature of agricultural contributions developed in the earlier work, and (2) the natural contributions which have been essentially overlooked in the previous investigations. The statistical technique of least-squares regression was used to examine the available historical data relating to the hydro-geologic-salinity relationship of the study area. Data from one of the larger irrigation systems, the Government Highline Canal, accounting for approximately 40 percent of total Valley diversions and irrigated acreage, were employed to represent the impact of agricultural sources. The potential salt pickup effects due to natural causes were evaluated with the aid of historical precipitation records.

The findings of this analysis are not conclusive, but the results raise a number of important policy implications. First, the absolute volume of dissolved solids added to the river varies considerably from year to year. During the period 1951-1972, the mean annual salt pickup in the study reach was about 540,000 tons. If an allowance is made for the normal contribution of salts from the major ungaged (perennial) tributaries in the reach, notably the Little Dolores River and Plateau Creek, the mean is nearer to 440,000 tons, or 160,000 below the generally accepted benchmark figure.

Second, the analysis of annual data indicates that net salt pickup in the Grand Valley reach decreased during the study period. This decreasing trend was found to be statistically significant but inversely related to irrigation water diversions and use. The simple fact that salt load and river discharge is highly correlated suggests that natural processes, whether they be explained by precipitation runoff or ground water interchange phenomena, have apparently been greatly underestimated. Although a precise estimate of the relative magnitudes of these sources will require a more detailed analysis, the significant associations found between precipitation and net pickup strongly suggest that the natural sources are responsible for more than just the 5 percent of the total salt pickup in the reach estimated by the generally accepted authorities.

Third, on the basis of statistical tests, deep percolation on farms was not found to be a very important source of salt pickup in irrigation return flows. This finding is especially meaningful since on-farm controls are believed to be the least-cost abatement strategy in the Upper Colorado River basin. However, due to the nature of the data and assumptions required to perform tests of this hypothesis, this conclusion should not be construed as conclusive, but warrants further,more careful examination.

Finally, the results implicate canal and lateral seepage as the apparent cause of salt pickup via irrigation return flows. Regression results,using quarterly data, is the only case, however, where seepage was found to be statistically significant and "positively" associated with salt pickup. The magnitude of seepage-induced salts remains to be identified.

It was not the purpose of this study to estimate empirically the actual amounts of salt loading by source. Regression analysis can generate such estimates, but this would require additional information. Nonetheless, the regression coefficient can be interpreted as a "rate of salt pickup" -- the change in net salts per unit change in the explanatory variable. In this form, the regression results are comparable to the earlier field investigations which have reported experimental estimates of pickup rates by type of pickup mechanism. Selected results of the regression runs are summarized in Table 27.

Net salt pickup associated with precipitation in a normal year (i.e., when precipitation is evaluated at its mean value), given the effects of time, is shown (in Part A) to range from 122,000 to 299,000 tons. Converting these estimates to tons per square mile of surface area in the

TABLE 27. EMPIRICAL ESTIMATES OF RATES OF PICKUP AND THE MAGNITUDE OF TOTAL SALT CONTRIBUTIONS FROM NATURAL AND MANMADE SOURCES

Explanatory Variable(s)a/	Significance Level of b	Rate of Net Salt Pickupb/ (Tons/Unit)	Range in Predicted Values of Salt Pickupc/ Low Est.	Mean	High Est.
			- - -(1000 Tons)- - -		
A. ANNUAL RELATIONSHIPS					
Precipitation	.10	25,150/Inch ± 14,490	85	202	318
Precipitation|Time	.04	26,270/Inch ± 11,040	122	211	299
Precipitation|(RD-ET)d/	.12	22,670 inch ± 13,670	72	182	291
Precipitation|Seepage	.10	26,300/Inch ± 15,130	90	211	332
Seepage	.03	4.54/AF ± 1.80	171	283	395
Seepage|Time	.19	2.47/AF ± 1.82	40	154	267
B. QUARTERLY RELATIONSHIPS					
Seepage (Apr.-June)	.02	5.16/AF ± 1.95	82	131	181
Seepage (July-Sept.)	.06	2.80/AF ± 1.40	44	84	133
Seepage (July-Sept.) (3 mo. lag)	.05	3.70/AF ± 1.78	61	117	173

a/ Results given for two and three variable cases. The slash (|) can be interpreted as ...."given the influence of time, etc., evaluated at its mean."

b/ Defined as the change in net salt pickup per unit change in the explanatory variable (the regression coefficient ± its standard error).

c/ Found by multiplying the mean of the variable by its regression coefficient. The standard error provides a high and low range on the estimate (a confidence interval of roughly 67 percent about the mean).

d/ (RD-ET) is a proxy for total irrigation return flows.

reach, this amounts to 40.6 and 99.6 tons per square mile , respectively. As pointed out in section B, this range brackets Elkins' [1976] estimate of the surface runoff contribution of about 58 tons per square mile. The estimated rate of salt pickup attributed to seepage ranges from about 2.5 to 4.5 tons per acre foot of seepage water on an annual basis. Using the quarterly relationships, part B, the pickup rate appears slightly higher for early season conditions and for a three month lag in the late season. These rates of pickup for seepage waters are not much different from those found by Kruse [1975] and Olsen [1976].

These inferences, drawn from the interpretation of the regression coefficients, tend to support the general validity of the conceptual model and the analytical approach used in this study. However, in closing, certain limitations of the results should be reviewed. One critical assumption in the analysis is that a single irrigation district or contiguous canal and lateral system can adequately reflect the cropping patterns, water use, seepage losses, etc., for the Grand Valley as a whole. Sufficient evidence to substantiate the validity of this assumption is not available. Secondly, because sound empirical data is generally unavailable except for the time period used in the analysis, there is a question as to the long term representativeness of the sampled data. Lastly, the conceptualization and formulations of the problem for analysis were, out of necessity, nonrigorous and somewhat simplistic.

Recommendations for Further Research

The findings reported in this chapter are not conclusive. In view of the announced time schedule of the programs for control of irrigation return flows in the Colorado River Basin, it is important that the relative importance of natural versus manmade sources of salinity be more clearly delineated. Two lines of inquiry to this end are noted below.

A first step would be to apply the same type of statistical analysis as was reported here to the Gunnison-Uncompaghre basin in western Colorado. Data from the gaging station at the mouth of the Gunnison River (at Grand Junction, Colorado), would provide the necessary information on salt loading. The area is quite similar to the Grand Valley in geology, climate and agricultural practices. The Uncompaghre and the Grand Vallies together are thought to contribute a majority of salinity from irrigation in the Upper Basin. Corroboration that natural sources of salinity are more important than has been thought previously, as we would anticipate from some of the relevant hydrologic data, would have important implications for the salinity control program.

A second recommended extension of our study would be to analyze daily observations. Since some natural sources (i.e., surface runoff) have more rapid effects on water quality than return flow phenomena, testing this hypothesis on the basis of available daily observations might uncover relationships which are masked when longer time periods are employed.

Finally, since we can claim neither statistics nor watershed hydrology as primary fields of expertise, such studies would probably be more productive if such specialists were drawn into the study design.

Section VII

APPENDIX

LITERATURE CITED

Anderson, J. C., R. J. Hanks, L. G. King, S. W. Childs, and J. R. Cannon (1974). "An Evaluation of Farm Practices as a Means to Control the Water Quality of Return Flow," Report No. 19, Agricultural Experiment Station, Utah State University, Logan, Utah.

Bishop, A. A., M. E. Jensen, and W. A. Hall (1967). "Surface Irrigation Systems," in Irrigation of Agricultural Lands, edited by Hagan, Haise and Edminster, No. 11 in the "Agronomy" series, American Society of Agronomy, Madison, Wisconsin.

____________, and H. B. Peterson (1969). "The Characteristics of Pollution Problems of Irrigation Return Flow." Contract No. 14-12-408, Federal Water Pollution Administration, U. S. Department of Interior.

Carter, H. O. and G. W. Dean (1961). "Cost-Size Relationships for Cash-Crop Farms in a Highly Commercial Agriculture," Journal of Farm Economics, Vol. 43, May.

Day, L. M. (1963). "Use of Representative Firms in Studies of Interregional Competition and Production Response," Journal of Farm Economics, Vol. 45, No. 5.

Decker, R. S. (1951). "Progress Report on Drainage Project," Lower Grand Valley Soil Conservation District, Mesa County, Colorado.

Draper, N. R. and H. Smith (1966). Applied Regression Analysis. (First edition). John Wiley and Sons, Inc., New York.

Elkin, A. D. (1976). "Grand Valley Salinity Study: Investigations of Sediment and Salt Yields in Diffuse Source Areas, Mesa County, Colorado." Review draft submitted to the State Conservation Engineer, Soil Conservation Service, Denver.

Ezekiel, M. and K. A. Fox (1965). Methods of Correlation and Regression Analysis (Fourth edition). John Wiley and Sons, Inc., New York.

Gray, S. L., J. R. McKean, J. Weber, and E. Sparling (1975). "Use of the Colorado Input-Output Model to Analyze the Impacts of Alternative Economic Scenarios on Output, Income, and Water Use and Employment in Colorado's Economy." A Report to the Colorado Energy Research Institute, available through the Department of Economics, Colorado State University, Fort Collins.

Gilley, J. R. (1968). "Intake Functions and Border Irrigation," M.S. Thesis, Department of Agricultural Engineering, Colorado State University, Fort Collins, Colorado.

Gross, A. D. (1965). "Condemnation of Water Rights for Preferred Uses--Replacement of Prior Appropriations?" Willamette Law Journal, 3(4): 263-283.

Hadley, R. F. (1976). Geological Survey, U.S. Department of Interior, Denver Federal Center, Denver, Colorado (Personal communication).

Harmston, F. K. and R. E. Lund (1967). Application of an Input-Output Framework to a Community Economic System. University of Missouri Studies, Volume XLII, the University of Missouri Press, Columbia, Missouri.

Howe, C. W. and D. Y. Orr (1974). "Effects of Agricultural Acreage Reduction on Water Availability and Salinity in the Upper Colorado River Basin," Water Resources Research, V. 10, No. 5.

Hyatt, M. L., J. P. Riley, M. L. McKee, and E. K. Israelsen (1970). "Computer Simulation of the Hydrologic-Salinity Flow System Within the Upper Colorado River Basin." Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah.

Iorns, W. F., C. H. Hembree, and G. L. Oakland (1964,65). "Water Resources of the Upper Colorado River Basin." General report and appendix, U.S. Geological Survey Professional Papers 441 and 442.

Jensen, M. E. and H. R. Haise (1963). "Estimating Evapotranspiration from Solar Radiation." In annual conference proceedings, American Society of Civil Engineers, Irrigation and Drainage Division.

Kelso, M. M., W. E. Martin, and L. E. Mack (1973). Water Supplies and Economic Growth in an Arid Environment: An Arizona Case Study, The University of Arizona Press, Tucson, Arizona.

Klapwyk, W. (1974). Manager, Grand Valley Water Users Association, Grand Junction (Personal communication).

Kneese, A. V. and C. W. Schultze (1975). Pollution, Prices, and Public Policy. Brookings Institute, Washington, D.C.

Kruse, E. G. (1975). "Alleviation of Salt Load in Irrigation Water Return Flow of the Upper Colorado River Basin." Annual Progress Report, Agricultural Research Service, U. S. Department of Agriculture, and U.S. Salinity Laboratory, Riverside, California.

Leathers, K. L. and W. T. Franklin (1975). "Irrigation Water Infiltration and Salt Pickup Mechanisms: Grand Valley, Colorado," unpublished manuscript, Department of Economics, Colorado State University, Fort Collins, Colorado.

______________ (1976a). "The Economics of Managing Saline Irrigation Return Flows in the Upper Colorado River Basin: A Case Study of Grand Valley, Colorado," Ph.D. dissertation in preparation, Department of Economics, Colorado State University, Fort Collins, Colorado.

______________ (1976b). "Costs and Returns to Crop Farming in the Grand Valley of Western Colorado." Manuscript in preparation, Department of Economics, Colorado State University, Fort Collins.

Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus (1958). *Hydrology for Engineers*. McGraw-Hill, Inc., New York.

Martin, W. E. and H. O. Carter. "A California Interindustry Analysis Emphasizing Agriculture," Giannini Foundation Research Report No. 250, University of California, Berkeley, 1962.

Mesa County Assessor's Office (1976). Grand Junction, Colorado (personal communication).

Moore, C. V. (1972). "On the Necessary and Sufficient Conditions for a Long-Term Irrigated Agriculture," *Water Resources Bulletin*, Vol. 8, No. 4, August.

Olsen, S. R. (1976). Research Leader, Soil Fertility and Management. Agricultural Research Service, U. S. Department of Agriculture, Colorado State University, Fort Collins (personal communication).

Oyarzabal-Tamargo, Francisco (1976). "Economic Impact of Saline Irrigation Water, Mexicali Valley, Mexico." Ph.D. dissertation, Department of Economics, Colorado State University, Fort Collins, Colorado.

Peskin, H. M. and E. P. Seskin (1975). *Cost Benefit Analysis and Water Pollution Policy*. The Urban Institute, Washington, D.C.

Public Law 89-321 (1965). Food and Agriculture Act of 1965, section 602, 79 Stat. 1206, as amended 7 U.S.C.A. 1838.

Rai, D. and W. T. Franklin (1973). "Program for Computing Equilibrium Solution in $CaCO_3$ and $CaSO_4$ Systems from Irrigation Water Compositions." CUSUSWASH Water Management Technical Report No. 29, Colorado State University, Fort Collins.

Richardson, H. W. (1972). *Input-Output and Regional Economics*. Redwood Press Limited, Trowbridge, Wiltshire, England.

Robinson, C. W. (1969). "Reclamation of Saline-Sodic Soils in the Upper Colorado River Basin." Bulletin 535-S, Colorado State University Experiment Station, Fort Collins, Colorado.

______________ and W. T. Franklin (1973). "A Survey of Salt Content of Irrigation Runoff," Colorado State University Experiment Station, PR 73-58, Fort Collins.

Schumm, S. A. and G. C. Lusbey (1963). "Seasonal Variation of Infiltration Capacity and Runoff on Hillslopes in Western Colorado." *Journal of Geophysical Research*, Vol. 68, No. 12.

Skogerboe, G. V. and W. R. Walker (1972). "Evaluation of Canal Lining for Salinity Control in Grand Valley." Environmental Protection Technology Services, EPA-R2-72-047, Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, D.C.

________________, W. R. Walker, J. H. Taylor, and R. Bennett (1974a). "Evaluation of Irrigation Scheduling for Salinity Control in Grand Valley," EPA-660-2-74-052 Series, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C.

________________, W. R. Walker, R. S. Bennett, J. E. Ayars, and J. H. Taylor (1974b). "Evaluation of Drainage for Salinity Control in Grand Valley," EPA-660-2-74-084 Series, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C.

Trelease, F. J. (1960). Severance of Water Rights from Wyoming Lands, Wyoming Legislature Resource Committee, Report No. 2, Cheyenne, Wyoming.

Tweeten, L. (1971). Foundations of Farm Policy. University of Nebraska Press, Lincoln, Nebraska.

Udis, B. et al. (1973). "The Interrelationship of Economic Development and Environmental Quality in the Upper Colorado River Basin: An Interindustry Analysis." Report to U.S. Department of Commerce, Economic Development Administration, University of Colorado, Boulder.

U.S. Bureau of Reclamation, Department of Interior (1967). "Quality of Water of Colorado River Basin." Progress Report No. 3, Salt Lake City, Utah.

____________________________________ (1972). "Colorado River Water Quality Improvement Program," Denver, Colorado.

____________________________________ (1973). "Quality of Water, Colorado River Basin," Progress Report No. 6, Washington, D.C.

____________________________________ (1974a). "Colorado River Water Quality Improvement Program," Status Report, Denver, Colorado.

____________________________________ (1974b). "Irrigation Management Services--Annual Report: Grand Valley, 1973." Western Projects Office, Grand Junction, Colorado (unpublished).

____________________________________ (1975). "Colorado River Improvement Program, Title II: Salinity Control Act." Progress Report, P.L. 93-320, Denver, Colorado.

U.S. Department of Agriculture and Colorado Agricultural Experiment Station (1957). "Soil, Water, and Crop Management Studies in the Upper Colorado River Basin," Annual Research Report, Colorado State University, Fort Collins.

______________________________ and the Colorado Water Conservation Board (1965). "Water and Related Land Resources, Colorado River Basin in Colorado." Denver, Colorado.

______________________________, Economic Research Service (1975). "Demand and Price Situation," Washington, D.C.

U.S. Department of Commerce (Selected years, 1951-1972). "Climatological Data: Colorado Annual Summaries." National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Asheville, North Carolina.

U.S. Environmental Protection Agency, Regions 8 and 9 (1971). *The Mineral Water Quality Problem in the Colorado River Basin*, 5 volumes (Summary report and appendices A,B,C,D), San Francisco, California.

U.S. Geological Survey (Selected years, 1952-1973). "Water Resources Data for Colorado, . . . and Utah, Parts I and II." Surface and water quality records, Denver, Colorado, and Salt Lake City, Utah. U.S. Government Printing Office, Washington, D.C.

Utah State University, Water Research Laboratory (1975). "Colorado River Regional Assessment Study, Parts 1-4," prepared for the National Commission on Water Quality, Logan, Utah, June 1975 (review draft).

Varble, G. L. (1969). "Grand Valley Trade Area, 1964." M.S. thesis, Department of Economics, Colorado State University, Fort Collins, Colorado.

Walker, W. R. and G. V. Skogerboe (1971). "Agricultural Land Use in the Grand Valley," Department of Agricultural Engineering, Colorado State University, Fort Collins, Colorado.

Walker, W. R. (1976). Department of Agricultural Engineering, Colorado State University, Fort Collins. (Personal communication.)

Wiscombe, E. (1975). Projects Manager, Upper Colorado Region, Western Colorado Projects Office, U.S. Bureau of Reclamation, Grand Junction, Colorado (personal communication).

Young, R. A. *et al.* (1975). "Economic and Institutional Analysis of Colorado Water Quality Management," OWRR Project No. 13-042-Colorado, Environmental Resources Center, Colorado State University, Fort Collins, Colorado (Completion Report Series, No. 61).

Table 1. LINEAR PROGRAMMING TABLEAU FOR CROP PRODUCTION MODEL I: 40 ACRE FARMS

Item	Unit	Crop Production Activities and Irrigation Processes										Constraint Levels	
		Corn		Small Grains		Sugar Beets		Perm. Pasture		Alfalfa			
		A	B	A	B	A	B	A	B	A	B	Maximum	Minimum
Net Revenue	$/Acres	107	103					9	5	48	44		
Irrigable Land	Acres	1.00	1.00					1.00	1.00	1.00	1.00	= 2,434	
Crop Acreage													
Corn	Acres	1.00	1.00									≤ 730	
Small Grains	Acres											≤	
Sugar Beets	Acres											≤	
Perm. Pasture	Acres							1.00	1.00			≤	289
Alfalfa	Acres									1.00	1.00	≤ 2,054	
Irrigation Water	AF/A	3.74	3.02					4.80	3.36	4.80	3.36	≤ 10,909	
Deep Percolation	AF/A	.73	.16					.55	.19	.38	.02	≥ 0	

Table 2. LINEAR PROGRAMMING TABLEAU FOR CROP PRODUCTION MODEL II: 80 ACRE FARMS

Item	Unit	Crop Production Activities and Irrigation Processes										Constraint Levels	
		Corn		Small Grains		Sugar Beets		Perm. Pasture		Alfalfa			
		A	B	A	B	A	B	A	B	A	B	Maximum	Minimum
Net Revenue	$/Acres	113	109			256	251	12	8	50	46		
Irrigable Land	Acres	1.00	1.00			1.00	1.00	1.00	1.00	1.00	1.00	= 4,932	
Crop Acreage													
Corn	Acres	1.00	1.00									≤ 2,601	
Small Grains	Acres											≤	
Sugar Beets	Acres					1.00	1.00					≤ 408	
Perm. Pasture	Acres							1.00	1.00			≤	425
Alfalfa	Acres									1.00	1.00	≤ 3,114	
Irrigation Water	AF/A	3.74	3.02			5.28	4.32	4.80	3.36	4.80	3.36	≤ 21,112	
Deep Percolation	AF/A	.73	.16			.64	.07	.55	.19	.38	.02	≥ 0	

Table 3. LINEAR PROGRAMMING TABLEAU FOR CROP PRODUCTION MODEL III: 130 ACRE FARMS

Item	Unit	Crop Production Activities and Irrigation Processes											Constraint Levels	
		Corn		Small Grains		Sugar Beets		Perm. Pasture		Alfalfa				
		A	B	A	B	A	B	A	B	A	B		Maximum	Minimum
Net Revenue	$/Acres	138	134	80	76	294	289	21	17	93	89			
Irrigable Land	Acres	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	=	16,624	
Crop Acreage														
Corn	Acres	1.00	1.00									≤	8,048	
Small Grains	Acres			1.00	1.00							≤		1,259
Sugar Beets	Acres					1.00	1.00					≤	696	
Perm. Pasture	Acres							1.00	1.00			≤		1,261
Alfalfa	Acres									1.00	1.00	≤	9,040	
Irrigation Water	AF/A	3.74	3.02	2.98	2.31	5.28	4.32	4.80	3.36	4.80	3.36	≤	69,307	
Deep Percolation	AF/A	.73	.16	.66	.06	.64	.07	.55	.19	.38	.02	≥	0	

Table 4. LINEAR PROGRAMMING TABLEAU FOR CROP PRODUCTION MODEL IV: 210 ACRE FARMS

Item	Unit	Crop Production Activities and Irrigation Processes										Constraint Levels	
		Corn		Small Grains		Sugar Beets		Perm. Pasture		Alfalfa			
		A	B	A	B	A	B	A	B	A	B	Maximum	Minimum
Net Revenue	$/Acres	171	167	92	88	413	408	35	31	116	112		
Irrigable Land	Acres	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	= 9,523	
Crop Acreage													
Corn	Acres	1.00	1.00									≤ 4,248	
Small Grains	Acres			1.00	1.00							≤	664
Sugar Beets	Acres					1.00	1.00					≤ 2,218	
Perm. Pasture	Acres							1.00	1.00			≤	626
Alfalfa	Acres									1.00	1.00	≤ 3,946	
Irrigation Water	AF/A	3.74	3.02	2.98	2.31	5.28	4.32	4.80	3.36	4.80	3.36	≤ 41,063	
Deep Percolation	AF/A	.73	.16	.66	.06	.64	.07	.55	.19	.38	.02	≥ 0	

Table 5. LINEAR PROGRAMMING TABLEAU FOR CROP PRODUCTION MODEL V: 370 ACRE FARMS

Item	Unit	Crop Production Activities and Irrigation Processes										Constraint Levels	
		Corn		Small Grains		Sugar Beets		Perm. Pasture		Alfalfa			
		A	B	A	B	A	B	A	B	A	B	Maximum	Minimum
Net Revenue	$/Acres	162	158	91	87	455	450	33	29	115	111		
Irrigable Land	Acres	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	=13,960	
Crop Acreage													
Corn	Acres	1.00	1.00									≤ 8,270	
Small Grains	Acres			1.00	1.00							≤	807
Sugar Beets	Acres					1.00	1.00					≤ 4,313	
Perm. Pasture	Acres							1.00	1.00			≤	295
Alfalfa	Acres									1.00	1.00	≤ 5,048	
Irrigation Water	AF/A	3.74	3.02	2.98	2.31	5.28	4.32	4.80	3.36	4.80	3.36	≤58,843	
Deep Percolation	AF/A	.73	.16	.66	.06	.64	.07	.55	.19	.38	.02	≥ 0	

Table 6. MONETARY TRANSACTIONS FOR THE GRAND VALLEY TRADE AREA, 1970

Sector Identification	PRODUCTION AND PROCESSING SECTORS																			LOCAL FINAL DEMANDS				OUTSIDE FINAL DEMANDS		TOTAL FINAL DEMANDS	TOTAL GROSS OUTPUT
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Capital Investments	Inventory Additions	State-Federal Governments	Exports		
1. RANGE LIVESTOCK	3300	1008					214			3623				5							1257	169		1063	28813	30045	39452
2. FED LIVESTOCK										602															5386	5386	5988
3. DAIRY	144	84					209			2490											42			27	483	510	3479
4. FORAGE AND FEED CROPS	1285	2172	71	5			43			201				34							33			220	3168	3388	7232
5. FOOD AND FIELD CROPS		50								2010											73			1110	5033	6143	8276
6. FRUIT AND SPECIALITY CROPS	130		58							1101			35								202			4	4073	4077	5603
7. OTHER AGRICULTURE	3		1	5	3		1			924											337				676	676	1950
8. FORESTRY	7										2870										143				2879	2879	5899
9. MINING									17060	3	836	10	32		43		1596	1380	28	463	1528	4890	2623	64209	43569	115291	138273
10. FOOD PROCESSING		747	150				190			122			2390	17	901					121	12000		1230	57	5917	7204	23846
11. MANUFACTURING	420	7	77	370	605	102	46	121	1920	293	725	30	3381	154	337	5376	273	2347	453	2204	5928	312	3158	2004	21576	27050	52307
12. WHOLESALE TRADE	391	3	38	50	108	43	12	39	818	160	122	60	1106	47	655	544	82	340	87	474	8440	1980	6496	394	8610	17480	30697
13. RETAIL TRADE	957	15	119	400	319	149	31	112	342	207	289	126	728	54	659	1005	145	408	385	178	49270	1260	9623	238	24455	35576	91714
14. AGRICULTURAL SERVICES	320	76	364	750	602	2529	46														234			8	100	108	5029
15. OTHER SERVICES	55	9	3	84	87	19	12	12	466	164	276	325	1667	30	2255	1668	429	742	859	2001	16210	78	1260	7866	37527	46731	74107
16. TRANSPORTATION	372	120	195	164	136	5	42		8269	45	1421	2620	3408	15	332	1740	78	1280	59	1640	7140	64		178	18799	19041	48118
17. UTILITIES	28	7	54	260	43	25	28		2241	319	870	350	2934	138	4213	182	2097	355	1239	1007	12700	32	6670	780	2839	10321	39403
18. CONSTRUCTION									108	21	252	173	926		738	199	436	24900	301	2130	7970	36700	12831	3360	7290	60181	98235
19. FINANCE	1530	78	82	250	56	36	27	128	669	72	330	1320	4636	73	1777	585	439	888	1688	6780	33500	1410		4481	11156	17047	71987
20. LOCAL GOVERNMENT	2560	17	327	280	388	216	39	155	1483	316	1089	485	1995	91	1406	732	2955	135	611	1218	17038			23100	1616	24716	58252
21. HOUSEHOLDS	19453	1467	1065	2907	4291	1012	540	3180	45639	4650	11819	10360	40840	1872	27110	18209	12203	22980	52900	26240	31520	2078		55768	14569	72415	413440
DEPRECIATION ALLOWANCES	3495	54	508	495	480	186	74	181	11214	597	2335	1120	3378	417	4380	4390	3910	1290	2250								40750
INVENTORY DEPLETIONS	700								3100	960	1433	3950	10582		12650		7590	13010			93180						53975
STATE & FEDERAL GOVERNMENTS	507	1	17	620	41	13	18	1570	1890	2230	4219	1450	1884	32	471	1660	1049	250	4745	416	61740			12200	4199	16399	101222
IMPORTS	3799	73	354	512	1116	460	370	405	42983	2062	25651	8310	11801	1701	16180	11747	6121	27890	6482	13300	51820	60160	10601	1980	71536	144277	378222
TOTAL INPUTS	39452	4622	3479	7232	8276	5603	1950	5899	133666	23846	52307	30697	91714	4687	74107	48118	39403	98235	71987	58252	412074	108733	54492	179839	322129	666541	1797456

Table 7. DIRECT INPUT COEFFICIENTS (Based on Table 6)

Sector Identification	PRODUCTION AND PROCESSING SECTORS																					LOCAL FINAL DEMANDS		OUTSIDE FINAL DEMANDS		TOTAL FINAL DEMANDS	TOTAL GROSS OUTPUT
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Capital Investments	Inventory Additions	State-Federal Governments	Exports		
1. RANGE LIVESTOCK	.0836	.1487					.1097			.1519				.0018							.0030	.0016		.0104	.0870	.0451	.0219
2. FED LIVESTOCK										.0252															.0167	.0061	.0033
3. DAIRY	.0036	.0140					.1072			.1084											.0001			.0002	.0015	.0008	.0019
4. FORAGE AND FEED CROPS	.0326	.3627	.0294	.0007			.0221			.0284				.0068							.0001			.0012	.0098	.0051	.0040
5. FOOD AND FIELD CROPS		.0083								.0043											.0002			.0062	.0156	.0092	.0046
6. FRUIT AND SPECIALTY CROPS	.0034		.0167							.0462			.0004								.0005				.0126	.0061	.0031
7. OTHER AGRICULTURE			.0001	.0007	.0004		.0006			.0387											.0008				.0021	.0010	.0011
8. FORESTRY	.0002										.0549										.0003				.0089	.0043	.0033
9. MINING									.1234	.0001	.0160	.0006	.0003		.0086		.0405	.0140	.0004	.0079	.0037	.0450	.0481	.3570	.1353	.1730	.0769
10. FOOD PROCESSING		.1247	.0431				.0995			.0251			.0261	.0034	.0122					.0021	.0290		.0226	.0063	.0184	.0108	.0133
11. MANUFACTURING	.0106	.0012	.0221	.0512	.0731	.0182	.0236	.0205	.0139	.0123	.0139	.0010	.0389	.0306	.0086	.1117	.0089	.0239	.0063	.0392	.0143	.0029	.0580	.0111	.0670	.0406	.0291
12. WHOLESALE TRADE	.0090	.0005	.0109	.0089	.0128	.0077	.0062	.0066	.0059	.0067	.0023	.0020	.0121	.0093	.0088	.0113	.0021	.0035	.0012	.0081	.0206	.0145	.1192	.0022	.0267	.0256	.0171
13. RETAIL TRADE	.0293	.0025	.0342	.0664	.0385	.0266	.0159	.0190	.0025	.0057	.0055	.0041	.0079	.0167	.0089	.0225	.0037	.0050	.0053	.0031	.1192	.0116	.1770	.0013	.0759	.0534	.0510
14. AGRICULTURAL SERVICES	.0081	.0127	.1046	.1037	.0727	.4514	.0236														.0006				.0003	.0002	.0020
15. OTHER SERVICES	.0014	.0015	.0009	.0116	.0135	.0034	.0062	.0070	.0024	.0069	.0053	.0106	.0181	.0076	.0304	.0347	.0109	.0076	.0119	.0344	.0392	.0007	.0231	.0437	.1165	.0701	.0412
16. TRANSPORTATION	.0094	.0200	.0560	.0227	.0164	.0009	.0215		.0080	.0019	.0272	.0053	.0371	.0030	.0045	.0361	.0020	.0130	.0008	.0082	.0173	.0046		.0010	.0584	.0286	.0268
17. UTILITIES	.0006	.0017	.0155	.0260	.0062	.0045	.0123		.0162	.0134	.0166	.0116	.0020	.0274	.0560	.0028	.0532	.0036	.0172	.0173	.0307	.0003	.1224	.0043	.0080	.0155	.0219
18. CONSTRUCTION									.0020	.0080	.0068	.0054	.0101		.0180	.0081	.0111	.2535	.0020	.0366	.0193	.3375	.2355	.0187	.0226	.0978	.0547
19. FINANCE	.0380	.0130	.0236	.0346	.0060	.0064	.0138	.0218	.0084	.0030	.0062	.0430	.0505	.0145	.0240	.0122	.0111	.0090	.0234	.1184	.0810	.0130		.0249	.0366	.0256	.0400
20. LOCAL GOVERNMENT	.0649	.0028	.0960	.0388	.0469	.0386	.0090	.0263	.0107	.0133	.0208	.0158	.0218	.0181	.0190	.0152	.0750	.0014	.0085	.0209	.0412			.1204	.0060	.0371	.0324
21. HOUSEHOLDS	.4931	.2450	.3061	.4020	.5185	.3234	.2810	.5391	.3301	.1950	.2260	.3375	.4453	.3722	.3636	.3784	.3097	.2335	.7349	.4505	.0762	.0191		.3101	.0452	.1086	.2300
TOTAL ABOVE	.7865	.9723	.7404	.7751	.8422	.8810	.7632	.6345	.5572	.7212	.3569	.5169	.6986	.5413	.5455	.6302	.5263	.5061	.8120	.7646	.4983	.4467	.8055	.9212	.7649	.7589	.6806
DEPRECIATION ALLOWANCES	.0886	.0117	.1449	.1484	.0180	.0332	.0379	.0308	.0839	.0250	.0446	.0365	.0368	.0890	.0591	.0912	.0992	.0131	.0313								.0227
INVENTORY DEPLETIONS	.0177								.0232	.0403	.0274	.1287	.1154		.1707		.1826	.1336			.2261						.0300
STATE & FEDERAL GOVERNMENTS	.0129	.0002	.0069	.0057	.0050	.0023	.0092	.2661	.0141	.0935	.0807	.0472	.0295	.0068	.0064	.0345	.0266	.0625	.0659	.0071	.1498			.0678	.0130	.0246	.0563
IMPORTS	.0963	.0138	.1018	.0708	.1348	.0835	.1897	.0687	.3216	.1200	.4906	.2707	.1207	.3629	.2183	.2441	.1953	.2839	.0906	.2283	.1258	.5533	.1945	.0110	.2221	.2165	.2104
TOTAL INPUTS	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 8. DIRECT AND INDIRECT TRANSACTIONS PER DOLLAR OF FINAL DEMAND (AND OUTPUT)

Sector Identification	PRODUCTION AND PROCESSING SECTORS 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. RANGE LIVESTOCK	1.1007	.2156	.0155	.0086	.0092	.0087	.1461	.0081	.0060	.1853	.0044	.0060	.0126	.0077	.0085	.0068	.0058	.0050	.0106	.0090	.0136
2. FED LIVESTOCK	.0009	1.0041	.0018	.0008	.0008	.0008	.0034	.0007	.0006	.0263	.0004	.0006	.0014	.0006	.0009	.0006	.0005	.0004	.0010	.0008	.0012
3. DAIRY	.0080	.0327	1.0081	.0037	.0039	.0036	.1225	.0034	.0025	.1145	.0018	.0025	.0062	.0029	.0040	.0029	.0024	.0021	.0044	.0039	.0057
4. FORAGE AND FEED CROPS	.0369	.3742	.0233	1.0024	.0016	.0041	.0322	.0010	.0007	.0280	.0005	.0007	.0017	.0076	.0011	.0008	.0007	.0006	.0013	.0011	.0016
5. FOOD AND FIELD CROPS	.0031	.0222	.0062	.0028	1.0030	.0028	.0115	.0027	.0020	.0883	.0014	.0020	.0048	.0023	.0031	.0022	.0019	.0016	.0034	.0030	.0044
6. FRUIT AND SPECIALITY CROPS	.0059	.0093	.0206	.0020	.0022	1.0020	.0092	.0019	.0014	.0511	.0010	.0014	.0035	.0016	.0021	.0016	.0014	.0012	.0025	.0021	.0032
7. OTHER AGRICULTURE	.0022	.0074	.0037	.0026	.0024	.0019	1.0064	.0019	.0014	.0412	.0010	.0014	.0028	.0015	.0019	.0015	.0013	.0011	.0024	.0020	.0031
8. FORESTRY	.0032	.0039	.0038	.0051	.0064	.0036	.0038	1.0029	.0026	.0033	.0569	.0019	.0041	.0031	.0017	.0080	.0019	.0030	.0025	.0043	.0027
9. MINING	.0093	.0101	.0094	.0108	.0102	.0089	.0087	.0077	1.1475	.0083	.0236	.0070	.0103	.0074	.0096	.0087	.0552	.0267	.0107	.0195	.0115
10. FOOD PROCESSING	.0343	.1623	.0721	.0314	.0336	.0310	.1340	.0297	.0219	1.0434	.0159	.0219	.0554	.0254	.0355	.0251	.0211	.0181	.0385	.0335	.0490
11. MANUFACTURING	.0484	.0644	.0648	.0882	.1098	.0608	.0635	.0473	.0435	.0547	1.0337	.0308	.0693	.0519	.0271	.1406	.0304	.0506	.0393	.0730	.0404
12. WHOLESALE TRADE	.0364	.0326	.0342	.0307	.0380	.0335	.0312	.0281	.0235	.0315	.0148	1.0189	.0341	.0255	.0260	.0302	.0184	.0181	.0290	.0318	.0350
13. RETAIL TRADE	.1521	.1604	.1384	.1761	.1586	.1370	.1281	.1264	.0844	.1185	.0648	.0857	1.1147	.0910	.0927	.1129	.0807	.0731	.1460	.1185	.1800
14. AGRICULTURAL SERVICES	.0171	.0633	.1183	.1061	.0752	.4539	.0465	.0021	.0016	.0476	.0011	.0016	.0034	1.0024	.0022	.0018	.0015	.0013	.0028	.0023	.0035
15. OTHER SERVICES	.0547	.0608	.0489	.0602	.0620	.0516	.0518	.0460	.0390	.0498	.0338	.0469	.0642	.0410	1.0666	.0742	.0457	.0377	.0685	.0846	.0706
16. TRANSPORTATION	.0457	.0678	0902	.0562	.0521	.0322	.0604	.0281	.0918	.0406	.0450	.1090	.0678	.0251	.0273	1.0648	.0268	.0369	.0350	.0608	.0423
17. UTILITIES	.0506	.0682	.0623	.0857	.0551	.0592	.0589	.0407	.0500	.0570	.0403	.0434	.0761	.0601	.0936	.0419	1.0876	.0310	.0702	.0656	.0644
18. CONSTRUCTION	.0367	.0360	.0328	.0329	.0352	.0312	.0301	.0300	.0240	.0253	.0236	.0305	.0441	.0230	.0380	.0318	.0402	1.3577	.0417	.0819	.0471
19. FINANCE	.1554	.1451	.1235	.1348	.1139	.1073	.1144	.1132	.0742	.1083	.0587	.1127	.1432	.0839	.0975	.0907	.0848	.0676	1.1400	.2172	.1459
20. LOCAL GOVERNMENT	.1299	.0962	.1496	.0957	.1050	.0971	.0929	.0747	.0507	.0898	.0506	.0541	.0746	.0573	.0622	.0595	.1157	.0328	.0717	1.0762	.0779
21. HOUSEHOLDS	.9823	.9899	.7851	.8571	.9486	.8427	.7992	.8642	.6428	.7486	.4611	.6380	.8407	.6377	.6657	.7099	.6130	.5286	1.1339	.9126	1.4569
HOUSEHOLDS (ADJUSTED)	.8924	.9858	.7788	.8550	.9458	.8410	.7941	.8617	.5602	.7175	.4461	.6262	.7542	.6362	.6241	.6667	.5636	.3893	.9947	.8480	1.0000
TOTAL MULTIPLIER	2.9137	3.6266	2.8127	2.7941	2.8270	2.9761	2.9548	2.4609	2.3118	2.9567	1.9314	2.2169	2.6350	2.1591	2.2674	2.4168	2.2312	2.2953	2.8552	2.8038	2.2599

☆ U.S. Government Printing Office: 1976-777-175/11 Region 8